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GENERIC VERIFICATION PROTOCOL FOR ADD-ON NO_x CONTROL TECHNOLOGIES UTILIZING OZONE INJECTION FOR STATIONARY COMBUSTION SOURCES

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1.0 INTRODUCTION

1.1 Environmental Technology Verification

The U.S. Environmental Protection Agency (EPA) has instituted the Environmental Technology Verification (ETV) Program to verify the performance of innovative technical solutions to problems that threaten human health or the environment. EPA created the ETV program to substantially accelerate the entrance of new environmental technologies into the domestic and international marketplaces.

ETV supplies technology buyers, developers, consulting engineers, and permitters with high-quality, objective data on the performance of new or improved technologies. This encourages more rapid protection of the environment with better and less expensive approaches.

ETV has established verification efforts in 12 pilot areas. In these pilot programs, EPA utilizes the expertise of verification partners to design efficient processes for conducting performance tests of environmental control technologies. EPA selects its verification partners from the non-profit public and private sectors, including laboratories, state agencies, and universities. Verification partners oversee and report verification activities based on testing that follows protocols developed with input from all major stakeholder/customer groups associated with the technology area.

The ETV goal is to verify the environmental performance characteristics of commercial-ready technologies through the evaluation of objective and quality-assured data so that potential purchasers and permitters are provided with an independent and credible assessment of what they are buying and permitting.

1.2 Air Pollution Control Technology Program

One of the 12 ETV pilot programs is the Air Pollution Control Technology (APCT) program. EPA's verification partner in the APCT program is Research Triangle Institute (RTI), a non-profit contract research organization with headquarters in Research Triangle Park, NC. The APCT program will verify the performance of commercial-ready technologies used to control air pollutant emissions. The initial emphasis of the APCT program is on technologies for controlling particulate matter, volatile organic compounds, nitrogen oxides (NOx), and hazardous air pollutants. As the program matures, more technologies will be added.

RTI will cooperatively organize and develop the APCT program for verification testing of air pollution control technologies. The APCT program will evaluate only those technologies that are ready for the marketplace.

The APCT program will develop generic verification protocols and specific test/quality assurance (QA) plans, conduct independent testing of technologies, and prepare verification test reports and statements for broad dissemination. A goal of the APCT program is to ultimately become self-sustaining, or "privatized," by operating on project-generated income (user fees) and other resources.

Of the NOx control technologies, the APCT program has selected NOx control technologies that utilize ozone injection for the initial verification. Ozone injection NOx control is typically used for small and medium stationary sources.

1.3 The NOx Control (Ozone Injection) Technology Program

Control of NOx emissions is of increasing interest. EPA recently completed a rulemaking to reduce over 1 million tons of NOx each ozone season and offered to develop and administer a multistate market-based NOx trading program to assist the affected States.[1] Achieving the new NOx standard will require additional control of NOx emissions from stationary sources. In addition, since a NOx emission level below the level mandated allows the generation of credits or allowances that may be sold on the market, pollution prevention becomes more cost effective, and innovations in less-polluting alternatives and control technology are encouraged. For these reasons, the Stakeholder Advisory Committee (SAC) recommended add-on NOx control technologies for small and medium size stationary combustion sources as a priority for verification.

This generic verification protocol covers a subset of that technology type; i.e., technologies that react ozone with NOx and scrub the resulting nitric acid. Sufficient ozone is injected into the flue gas to achieve the desired stoichiometry. The reaction zone residence time required to achieve a given NOx conversion depends on the temperature of the flue gas and varies depending on whether the technology recovers heat before or after ozone injection. The insoluble stack gas NOx (largely nitric oxide (NO) and nitrogen dioxide (NO_2)) reacts with the ozone to form dinitrogen pentoxide (N_2O_5), which is soluble in water. The NOx control is accomplished through the following chemical reactions:

$$NO + O_3 \quad NO_2 + O_2 \tag{1}$$
$$NO + \tfrac{1}{2} O_2 \quad NO_2 \tag{2}$$
$$2NO_2 + O_3 \quad N_2O_5 + O_2 \tag{3}$$
$$N_2O_5 + H_2O_{(g)} \quad 2HNO_3 \tag{4}$$

where: O_3 = ozone,
O_2 = oxygen,
$H_20_{(g)}$ = water vapor, and
HNO_3 = nitric acid.

A wet scrubber at the end of the train collects the N_2O_5 and any gaseous HNO_3 into an acidic waste stream. In addition to NOx removal, such technologies have potential for removal of other

[1]Twenty-two of the easternmost States and the District of Columbia were determined by EPA in the transport rule-making (63 FR 57356) to make a significant contribution to non-attainment or interfere with maintenance in another jurisdiction. Each of these States has been assigned a statewide NOx emissions budget and must submit a plan including controls that will be implemented to meet its specified budget. Each State has complete discretion to develop and adopt a mix of control measures appropriate for meeting its assigned emissions budget. Compliance with the emissions reductions requirements for the transport rule-making will begin on May 1, 2003.

acid gases (such as sulfur oxides and carbon monoxide) and volatile organic compounds (VOCs). Control of these other pollutants is not a topic included in this generic verification protocol.

This generic verification protocol includes all not-site-specific information concerning testing this type of NOx control technology, as applied to small- and medium-sized stationary combustion sources. Other site- or case-specific information also must be addressed in conducting verification testing. That information will be covered in a test/QA plan that provides a detailed plan to implement each verification test and document test procedures. Testing will be performed using test/QA plans based on this generic verification protocol, which was developed with input from a technical panel of qualified stakeholders. Test results will be presented as reports and verification statements.

1.4 Quality Management Documents

Management and testing within the NOx Control Technology Program are performed in accordance with procedures and protocols defined by a series of quality management documents. These include EPA's Quality and Management Plan (ETV QMP) for the overall ETV program (EPA, 1998a), the Quality Management Plan (QMP) for the overall APCT program (RTI, 1998), the Generic Verification Protocol for Add-on NOx Control Technologies (this document), and test/QA plans prepared by the test organizations.

EPA's ETV QMP lays out the definitions, procedures, processes, inter-organizational relationships, and outputs that will ensure the quality of both the data and the programmatic elements of ETV. Part A of the ETV QMP contains the specifications and guidelines that are applicable to common or routine quality management functions and activities necessary to support the ETV program. Part B of the ETV QMP contains the specifications and guidelines that apply to test-specific environmental activities involving the generation, collection, analysis, evaluation, and reporting of test data.

APCT's QMP describes the quality systems in place for the overall APCT program. It was prepared by RTI and approved by EPA. Among other quality management items, it defines what must be covered in the generic verification protocols and test/QA plans for technologies undergoing verification testing.

Generic Verification Protocols are prepared for each technology to be verified. These documents describe the overall procedures to be used for testing a specific technology and define the critical data quality objectives (DQOs). The document herein is the generic verification protocol for add-on NOx control technologies that use ozone injection to control emissions from small- and medium-sized stationary combustion sources. It was written by the APCT program with input from a technical panel and approved by EPA.

Test/QA plans are prepared by the test organizations. The test/QA plan describes, in detail, how the testing organization will implement and meet the requirements of the generic verification protocol. The test/QA plan also sets DQOs for non-critical measurements that are specific to the site of the test. The test/QA plan addresses issues such as the test organization's management organization, test schedule, documentation, analytical methods, data collection

requirements, calibration, and traceability, and it specifies the QA and quality control (QC) requirements for obtaining verification data of sufficient quantity and quality to satisfy the DQOs of the generic verification protocol. Section 10 of this generic verification protocol addresses requirements for the test/QA plan.

2.0 OBJECTIVE, SCOPE, AND VERIFICATION PARAMETERS

2.1 Objective

The objective of the Add-on NOx Control ETV Program is to verify, with high data quality, the emission rate performance of NOx control technologies that are based on ozone injection, as applied to small- and medium-sized stationary combustion sources. The NOx control technologies will be verified within a specified range of applicability, and verification reports and statements will be produced for dissemination to the public.

2.2 Scope

Testing will be performed on add-on control devices that use ozone injection and are applied to small- or medium-sized stationary emission sources. The verification tests will gather information and data for evaluating the performance of the technologies as claimed by the vendors and the technologies' associated environmental impacts and resource requirements. The scope will, in most cases, cover four principal study questions:

1. What is the performance of the technology relative to the manufacturer/vendor's statement of capabilities (e.g., NOx emission concentration in ppmv)?
2. What are the test conditions (a range) over which the performance is measured (e.g., flue gas flow rate, temperature in the reaction zone, inlet NOx concentration, oxidizing agent injection rate, and percent of rated capacity)?
3. What are the associated environmental impacts of operating the technology within this range (e.g., effects on other pollutant emission rates)?
4. What are the resources associated with operating the technology within this range (e.g., energy, water, ozone)?

Question 1 is the critical question for this verification, and thus performance measurements are critical measurements. The data quality objectives (DQOs) for question 1 are specified in this protocol, and are intended to apply to multiple test sites. Measurements to answer question 2 require sufficient accuracy to support the DQOs for question 1, but are not critical. These measurements may utilize plant instrumentation, and thus specific DQOs will be part of the test/QA plan rather than included in this generic verification protocol. However, high quality measurements are important because these measurements will establish the boundaries of the envelope within which performance is being verified. Questions 3 and 4 are non-critical and may be answered based on estimates and available instrumentation. When appropriate, DQOs for measurements addressing questions 3 and 4 will also be stated in the test/QA plan.

2.3 Data Quality Objectives (DQOs)

The critical measurement for add-on NOx control technologies utilizing ozone injection has been identified to be control device NOx emission concentration. As is described in Sections 5 and 6 and illustrated in Appendix C, the performance of a NOx control technology will be verified using an experiment statistically designed to achieve this critical DQO within the performance range tested. For the NOx emission concentration, the test/QA plan will include measurements sufficient to allow determination of the technology's overall NOx emission within ± 10% of the mean emission concentration above 5 ppmv, ±25% below 5 and above 2 ppmv, and ± 50% below 2 ppmv. The DQO is to be computed as the half-width of the 95% confidence interval of the mean, divided by the mean, or, equivalently, as the product of the standard error of the mean and the appropriate Students-t value divided by the mean. All measurements apply within the performance envelope being verified. The NOx emission concentration will be measured using EPA Method 7E, which is the reference standard for NOx emissions, and thus each measurement is taken to be without bias.

Unfortunately, no published data exist to allow evaluation of whether the critical NOx DQO specified in the paragraph above can be attained with a test program of modest duration. In all likelihood, the NOx DQO can be met at some level of testing, but other constraints on the ETV process require that the test cost be commensurate with the benefit derived from the verification. For this reason, the DQOs specified in this draft protocol must be considered tentative until field data are available to allow evaluation of the approach taken. Two of the three hypothetical data sets presented in Appendix C do not meet the critical NOx DQO.

Should the verification test be conducted and the critical NOx DQO not be met due to excessive data variability, the verification partner and testing organization will present the data to the vendor and discuss the relative merit of various options. The two primary options will be either to continue the test to obtain additional data, with resulting increases in cost to all parties, or to terminate the test and report the data obtained.

Specific DQOs will also be included in each test/QA plan for all measurements addressing the first two principal study questions. Associated measurement DQOs are specified in EPA Method 7E. The quality of measurements for questions 3 and 4 will be addressed through numeric DQOs when possible or through discussions when numeric estimates are not possible. Specific measurement DQOs may vary between different test/QA plans written to conform to the above critical NOx DQO.

While not critical, accurate measurement of test conditions such as flow rate, temperature, and inlet NOx is important because the measurements set the boundaries of the envelope within which the verification applies. Plant instrumentation may be used to make the measurements provided it is found to be adequate and has a current calibration. Parallel calibrated instrumentation should be used whenever practical. Measurement DQOs will be set after inspection of the test site and specified in the test/QA plan. The potential for measurement bias should be evaluated by inspection and experience. QC procedures and technical assessments will evaluate measurement bias during verification testing for those measurement parameters where the potential for bias has been identified.

The uncertainties outlined above require that the DQOs expressed in this draft generic verification protocol be reviewed following completion of the first tests and analysis of the results. The DQOs may need to be revised for the final version of this document.

3.0 VERIFICATION TESTING RESPONSIBILITIES

This verification testing program is conducted by the APCT program, under the sponsorship of the EPA, with the participation of technology manufacturers/vendors. The APCT program is operated under a cooperative agreement by the Research Triangle Institute (RTI), the ETV verification partner. RTI's role as verification partner is to provide technical and administrative leadership and either conduct or manage the conduct of verification testing and reporting. Various subcontractors have roles in the APCT program under RTI's management. In particular, the Midwest Research Institute, MRI, is the testing organization designated to conduct most field testing under the APCT program during the period of EPA-subsidized verification testing. Site-specific verification test/QA plans are prepared to meet the requirements of generic verification protocols, such as this one, approved by the APCT program.

The test/QA plan will include a figure that presents the test program organization and major lines of communication. Based on the figure, the plan will identify the testing organization and any other test participants. The plan will provide a table listing the name, affiliation, mailing address, telephone and fax numbers, and e-mail address of each participant. The organizations involved in verification of add-on NOx control technologies utilizing ozone injection are the EPA, RTI, Midwest Research Institute (MRI), and the technology manufacturer/vendor. (MRI is the sole test organization conducting field testing as part of the APCT program as of the date of this generic verification protocol.)

The primary responsibilities for each organization involved in the test program are:

- The EPA, following its procedures for ETV, reviews and approves generic verification protocols, test/QA plans, verification reports, and verification statements.
- The APCT program prepares the generic verification protocol, provides oversight of the testing organization, reviews the test/QA plans, and jointly with EPA reviews and approves the verification test reports and verification statements.
- The testing organization will prepare the site-specific test/QA plans, coordinate test details and schedules with the manufacturers/vendors, conduct the tests, and prepare and revise draft test reports and draft verification statements. The testing organization QA staff will be responsible for conducting internal QA on test/QA plans and reports.
- EPA and/or APCT program QA staff will conduct technical assessments of the test organization's tests and products.
- The technology manufacturers/vendors are responsible for providing complete, field-ready (operating in the field) equipment for verification testing; providing logistical and technical support, as required; and

assisting the testing organization with operation and monitoring of the equipment during the verification testing. A manufacturer must supply a verifiable statement of performance capability of the technology to be tested (see section 4.0). Each manufacturer/vendor will be responsible for bearing a portion of the test cost as defined by a contract or letter of agreement with RTI as APCT program verification partner.

4.0 TECHNOLOGY CAPABILITIES AND DESCRIPTION

The test/QA plan must contain a statement by the technology manufacturer/vendor of performance capabilities to be evaluated in the verification testing. The statement must be specific and verifiable by statistical analyses of the data. This statement must give the intended range of application of the technology, its known limitations, and the expected advantages for the technology relative to competing technologies. Because market niches for NOx control technologies may exist based on technology cost or reliability to reach particular levels of control, or on absolute NOx emission performance, statements of performance might be stated in various ways. For example, a NOx control technology that was focused on providing a very low emission concentration might provide a performance statement such as:

> "This ozone injection NOx control technology is capable of achieving a NOx emission concentration of .....when operated at....[specify process operating conditions]."

On the other hand, a NOx control technology might be marketed as providing reliable and consistent NOx emissions at particularly low inlet NOx under stated operating conditions while also providing stable and reliable control performance (albeit with higher NOx emissions) at higher NOx inlet conditions for another set of operating conditions. A performance statement reflecting this technology might be:

> "This ozone injection NOx control technology is capable of achieving a NOx emission concentration of _____ ppmv when operated at an inlet NOx concentration of _____ ppmv and [specify process operating conditions] and of controlling NOx emissions to below _____ ppmv when operated at an an inlet NOx concentration of _____ ppmv and [specify different process operating conditions]."

An unacceptably vague statement of performance capabilities would be:

> " This technology is capable of meeting the _____ rule on a consistent and dependable basis."

The test/QA plan will also describe the technology to be verified. The description, provided by the technology manufacturer/vendor, must include: technology name, model number, manufacturer's name and address, electrical requirements, serial number or other unique identification, warning and caution statements, capacity or output rate, and other information necessary to describe the specific technology. The performance guarantee coupled with

operating conditions will express the actual installation size if design parameters are proprietary. The test/QA plan will also include a draft verification statement, based on Appendix D, and be customized to the specific technology being verified and measurements being made.

Other descriptive information the vendor may provide for inclusion in the verification report can address the logistical, human, and economic resources necessary to install and operate the technology. Some examples are:

Installation requirements:
- footprint (space) occupied
- installation time
- site modifications (piping, duct work, electrical, structural, roadways)
- startup and shakedown time
- ancillary equipment, if any
- any other special requirements

Operator qualifications / training / safety
- qualifications needed to operate and service the technology
- amount and type of training needed for operation and maintenance
- special safety considerations

Maintenance requirements
- recommended maintenance procedures
- spare parts

Operation
- labor requirements
- chemicals and other consumable feedstocks and reactants
- energy use
- ancillary equipment requirements

Secondary emissions
- air
- water
- solid waste

Technology's life expectancy

5.0 TEST PROGRAM

The objective of verification testing is to evaluate air pollution control technologies for performance relative to the manufacturer/vendor's statement of technology capabilities (e.g., NOx emission rate) and relative to applicable regulations. (While the ETV program is not regulatory and an ETV test is not a compliance test, measurements that relate directly to regulations are of primary interest to most manufacturers/vendors.) Also, the environmental impacts of operating the technology (e.g., other pollutants emitted) and energy and environmental resource requirements will be evaluated. All tests will be conducted under steady-state operation during the test period. The specific operating conditions used during the verification testing will be documented as part of the verification process.

The two sections below will discuss the overall test design to achieve the verification objectives followed by a discussion of test parameters that can be considered. Detailed descriptions and a schedule for all the preparation for, conduct of, and reporting related to the test design will be given in the test/QA plan.

5.1 Test Design

A verification test must be designed to determine the performance of an APCT in specified terms and of known quality, and to define the applicability bounds of the verification. Four major factors to consider in the test design are:

1. The scale of the technology verification test,
2. Control equipment operation and inlet conditions during the tests,
3. Sample locations and sampling and measurement methods, and
4. The number, frequency, and duration of measurements.

5.1.1 Technology Verification Test Scale.

The possible options for technology verification test scale are full-scale installation, a pilot-scale (transportable) device operated on a slipstream at a full-scale facility, and a pilot-scale device operated at a controlled laboratory facility (e.g., EPA ORD's combustion facilities). (In this context, pilot-scale is taken to mean a small, transportable implementation of the technology that scales to its intended maximum size following established engineering scaling factors, or a single module of a technology that scales by adding additional modules. Decisions regarding the acceptability of pilot-scale units will be made by the APCT program, which must be convinced that the verification is applicable to its proposed use.) Factors that will influence the choice of verification scale include:

- The scale and nature of the specific equipment available for testing. This may be different for each verified technology,
- The desire to test an actual versus a simulated pollutant source,
- The need to control the source to support testing under varied conditions,
- Test costs, and
- Practical source testing constraints.

A full-scale facility will provide a test that best matches real world conditions but may offer limited flexibility to test the device under as wide a range of conditions as a vendor may request. A laboratory facility provides the most control of source and device operating conditions which allows the test to cover the broadest range of conditions but is less representative of real world conditions. A pilot device on a slipstream at a full-scale facility provides a compromise between the two other approaches.

5.1.2 Other Test Factors.

The other three major factors listed above -- technology operation, measurement methods, and number and type of measurements -- must also be considered in the experimental design.

They are also the sources of variability that can lead to uncertainty in the verification statement.

Control technology operation, the second factor, refers to the conditions at which the actual tested equipment is operated during the technology verification test. The range of these operating conditions determines the breadth of applicability for the verification test and hence of the verification statement. Key operating parameters, along with their expected range of values for the desired applications, must be identified and included in the test design.

Sample collection and measurement methods affect the data precision and, consequently, the data quality and applicability range of the verification statement. The NOx test method chosen (EPA Method 7E, 40 CFR Part 60, Appendix A) is the reference method that will be used to test any NOx air pollution control technology after its installation to determine compliance with a regulation. Measurements of other pollutants will also be made using EPA reference methods whenever such methods are available. Measurements of other parameters will also follow accepted testing practice standards whenever available. Measurement methods proposed for use in add-on NOx verification testing are discussed in Section 5.2. These methods will be used unless field circumstances require substitution of alternate methods; such substitution will be clearly noted and explained in the test/QA plan.

The number and length of test runs is set based on statistical experimental design considerations. These are discussed further below in Section 5.1.4 and in Section 6.3.

5.1.3 Limitations to Proposed Verification Testing.

Sources of potential variability in a verification result that will not be addressed for reasons of cost and practical difficulty are:

1. Change in performance over time. The verification will address performance only during a one-time test.
2. Performance differences between different installations of the NOx control technology being verified.

5.1.4 Statistical Verification Test Design Considerations

The remainder of this section describes the recommended experimental design process, and Section 5.1.5 applies that process to a specific example. Several assumptions are made to allow a specific example to be presented. The same approach will be used to develop the design for each verification test conducted under this generic verification protocol.

Two primary measures may be used to evaluate NOx control technology performance. One measure is the NOx emission concentration in parts per million by volume (ppmv). The other is the NOx removal efficiency. As recommended by the technical panel, NOx emission concentration was chosen as the performance measure of primary interest.

The basic experimental design will be to test the control technology by performing tests under different sets of field controllable test conditions that exercise the technology over a range

of operation within which performance will be verified. Operation outside that range may well be possible, but the verification statement will not apply. For an ozone injection NOx control technology, three parameters have been identified that can be controlled and are expected to affect performance. These are the inlet NOx concentration (IN NOx), the temperature at the point of ozone injection (TEMP), and the flow rate (FLOW), which for a given technology installation is directly related to residence time. The verification tests will measure the effects of IN NOx, TEMP, and FLOW on the NOx emission concentration (OUT NOx) within the operating range bounded by the upper and lower values of these independent parameters.

In the test/QA plan, statistical experimental design techniques will be used to design the most efficient test design – that which will provide the most information for the least number of tests. These techniques are most powerful when the mathematical form of the relationships between the independent parameters and dependent performance measure is known. Lacking that information, a linear relationship can be assumed, the experiment designed and data analyzed under that assumption, and the assumption then examined. It may be that the independent parameters are not equally important, which will simplify the analysis.

As discussed in Section 2.3, controlling the cost of verification testing is important to the viability of the APCT program. The NOx technical panel has determined that the cost of a field test program that is about 1 week in duration leads to an overall verification test whose cost is reasonable, given the value of that test to the manufacturer. Based on field test experience, the number of independent steady-state tests of NOx control equipment that can be conducted within a week of field time is estimated to be roughly 16 tests.

The balance of this section is based on a 2 x 2 x 2 factorial test design, which is appropriate when all three independent parameters are roughly equally important over the operating range, and provides a good starting point. Other designs -- such as partial factorials or blocked experiments -- may be better for another test/QA plan depending on the level of understanding of the process. The test/QA plan will be written to use all available process information to provide as efficient a test as possible.

A 2 x 2 x 2 factorial design uses each of the three parameters at two levels (low and high). The low and high values bound the operating range over which the verification applies. Each full replication of the factorial design requires eight test runs. While a single replication could be used, at least 2 replications are recommended, giving 16 test runs. Table 1 gives an example of a generic 2 x 2 x 2 factorial design. To the extent that it is practical, the order of the runs should be randomized as should the assignment of the low and high levels. As required by the DQO in Section 2.3, the product of this test design will be the verified mean NOx emission concentration(s) and the 95% confidence interval of the mean for the specified operating range.

Table 1. Factorial Experimental Design

Run	Inlet NOx	Temperature	Flow†
1	Low	Low	Low
2	Low	Low	High
3	Low	High	Low
4	Low	High	High
5	High	Low	Low
6	High	Low	High
7	High	High	Low
8	High	High	High

†Flow is the field measurable operating parameter which controls residence time for a given installation. High flow corresponds to low residence time.

This factorial design allows for statistical significance tests to determine whether the performance measure (i.e., outlet ppmv of NOx) varies significantly with any of the three parameters (see Section 6.3 for an example calculation). Further, provided that at least 2 replicates for a total of 16 test runs are done, the significance of interactions between the parameters can also be tested. If the performance does not change significantly with a parameter, then the results are valid for the range of that parameter covered by the test. If the performance does vary significantly with some parameter, then the statement of the results of the test must include information indicating the dependence of the performance on the operating parameter.

The DQO for NOx emission concentration is met when the 95% confidence interval of the mean has the specified width. The confidence interval for the outlet NOx level depends on several things: the variability of the NOx measurement, the desired level of confidence, the number of degrees of freedom for error, and the number of runs. Figure 1 illustrates how the half-width of the confidence interval about the mean NOx concentration varies with the number of test runs for three confidence levels within the expected test range and a reasonable variability. The three independent parameters are taken to be significant, and the NOx emission concentration mean is computed over all tests. Thus Figure 1 sheds light on the question of whether 16 test runs are likely to be sufficient.

The degrees of freedom are the number of test runs, reduced by 1 for the overall mean and further reduced by 1 for each significant parameter. For Figure 1, three factors were assumed significant; consequently, the degrees of freedom are the number of runs minus 4. Thus, when the number of runs is 8, corresponding to a single replicate of the test design, the assumed number of degrees of freedom is 4; while if 2 complete replicates are done for a total of 16 runs, the number of degrees of freedom is 12.

The half-width is the range on either side of the mean outlet NOx level within which data points are estimated to fall for the specified confidence level. The figure is a reasonably realistic

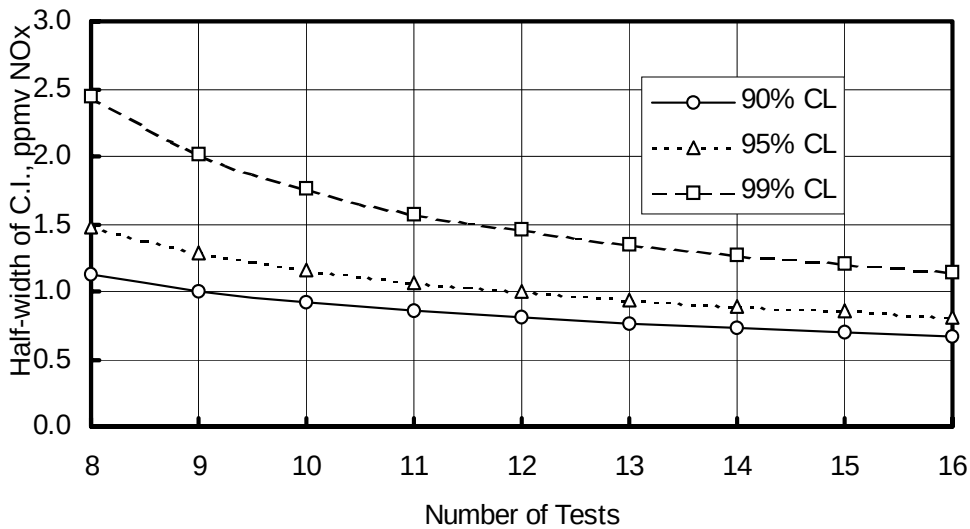

Figure 1. Half-width of the confidence interval on the mean NOx emission concentration (computed assuming about 90% NOx removal, true NOx emission of 10 ppmv, NOx measurement standard deviation of 1.5 ppmv, and three significant interactions) for 3 confidence levels (CL).

illustration, based on engineering judgment and test experience, of confidence intervals that may be determined from a verification test. The assumptions made to compute the specific values in Figure 1 are that the true outlet NOx level is 10 ppmv, that the standard deviation of the NOx measurement is 1.5 ppmv, and that there are three significant interactions. [Hung and Campbell (1998) assert that the error in the NOx measurement could be as high as 25% for outlet concentrations below 5 ppmv.]

The half-width of the confidence interval was then computed as the product of the standard deviation and the Students-t value appropriate for the degrees of freedom divided by the square root of the number of tests.

Figure 1 shows the half-widths of confidence intervals for three different confidence levels. The upper line corresponds to a confidence level of 99%, the middle to 95%, and the lower line to 90%. Assuming that two complete replications of the design were done, an expected 95% confidence interval for the outlet NOx level can be estimated from the figure. For example, take the middle line corresponding to the 95% confidence level. For a fully replicated 2x2x2 factorial test, the total number of runs is 16. Go to the right side of the chart and up to the 95% curve. Read back to the left axis to see that the half-width is estimated to be about 0.8 ppmv. The estimated 95% confidence interval for the outlet NOx level is 10 ± 0.8 ppmv (or from 9.2 to 10.8 ppmv) for this example in which the NOx emission concentration is 10 ppmv.

5.1.5 Application of Experimental Design Process to a Specific Example.

The experimental design process described above will now be applied to a specific set of

performance claims. Assume that a manufacturer/vendor presents the following set of performance claims for a process:

> "This ozone injection NOx control technology is capable of achieving a NOx emission concentration of 1 ppmv when operated at an inlet NOx concentration of 55 ppmv, ozone injection temperature of 290°F, and a flow rate of 20,000 cfm; the controlled NOx emissions are below 10 ppmv when operated at an an inlet NOx concentration of 300 ppmv, 310°F, and 30,000 cfm."

This set of performance claims can then be verified by setting up the experimental matrix with the indicated high and low values of inlet NOx concentration, temperature, and flow rate for the particular test site where the technology is installed. In addition to the statement above, the performance claims would also include a description of the combustion source and fuel, its operation, and other operating features. The test/QA plan would then consist of a detailed schedule of tests and data required to conduct this verification test by controlling the operation, to the extent possible, to match the proposed verification operating range limits.

Results from a test using a fully replicated 2x2x2 experimental design with hypothetical experimental data sets are reported in Section 6.3, and additional examples are given in Appendix C. (There are no known published data sets in which this type of factorial experimental design was used.) These data sets include three different levels of variability in all four experimental parameters – inlet NOx, outlet NOx, temperature, and flow rate. While hypothetical, the data sets are not arbitrary. They reflect the experience of the testing organization. They generally support the expectation that a 2x2x2 test matrix will provide NOx emission concentration data meeting the DQO stated in Section 2.3. However, field process variability cannot be accurately taken into account. For this reason, confirming that acceptable levels of process variability exist in the field will be an important goal of the pretest survey, and the experimental design will be finalized based on the results of that survey. While preliminary calculations and cost estimates will be based on the expectation of using a fully replicated 2x2x2 test matrix, in practice additional tests may be required to narrow the confidence interval.

5.2 Test Parameters

Measurement parameters to consider in the verification tests fall into four categories:

- Performance factors (e.g., direct emission measurements of inlet and outlet NOx),
- Associated impacts (e.g., ozone slip, wastewater discharge),
- Associated resource usage (e.g., total energy usage, fuel usage), and
- Test conditions documentation (e.g., fuel type, fuel flow rate, air flow rate, percent of rated capacity, combustion temperature, ozone injection rate, and ambient conditions).

Table 2 shows examples of factors to be verified, parameters to be measured for each factor, and the measurement method for each parameter (i.e., the standard test method for each parameter, if applicable). Measurement methods and procedures are presented in Appendix A of this protocol.

Table 2. Example Measured Parameters.

Factors to be Verified	Parameter to be Measured	Measurement Method	Comments
Performance Factors			
NOx emissions	Outlet NOx conc.	EPA Method 7E (40 CFR 60 App. A)	
NOx removal efficiency	Inlet and outlet NOx concentrations	EPA Method 7E (40 CFR 60 App. A)	
NOx mass emission rate	Inlet/outlet stack gas volumetric flow rate	EPA Methods 1 & 2 for velocity; 3, 3A, or 3B for O_2 and CO_2; and 4 for moisture (40 CFR 60 App. A)	Needed for mass emission rate calculation
	NOx emission rate	EPA Method 19 (40 CFR 60 App. A)	Alternative to measuring stack gas velocity
Associated Impacts			
Ozone slip	Outlet ozone conc.	NIOSH Method 154	Potassium iodide solution in a midget impinger train; light sensitive
	Outlet ozone conc.	UV photometric analyzer	Alternative to wet chemistry method; analyzer provided by APCT vendor
Carbon monoxide (CO) emissions	Inlet/outlet CO conc.	EPA Method 10 (40 CFR 60 App. A)	
Volatile organic compounds (VOC) emissions	Inlet/outlet VOC conc.	EPA Methods 25A and 18 (40 CFR 60 App. A)	Use Method 25A for total hydrocarbons and 18 for methane and ethane
Sulfur oxides (SO_x) emissions	Inlet/outlet SO_x conc.	EPA Methods 6, 6C, or 8 (40 CFR 60 App. A)	
Chlorine (Cl_2) emissions	Inlet/outlet Cl_2 conc.	EPA Method 26A (40 CFR 60 App. A)	
Wastewater	Concentration of acids	ASTM E70-90 pH meter	ASTM D1067-92 may be an acceptable alternative; EPA SW846, Method 9040B
	Flow rate	Water flow meter	Orifice plate, magnetic flow meter, manual gravimetric or volumetric measurement
	Total dissolved solids (TDS)	40 CFR 136 Method 160.3	
	Chemical oxygen demand (COD)	40 CFR 136 Method 410.4	

(continued)

Table 2. (continued)

Factors to be Verified	Parameter to be Measured	Measurement Method	Comments
Associated Resource Usage			
Energy consumption of ozone generator	Energy usage	ASTM E929-83 (1988) kilowatt-hour meter	ECM 1200 or 400 Energy consumption monitor from Brultech Research
Energy consumption of fan	Energy usage	ASTM E929-83 (1988) kilowatt-hour meter	ECM 1200 or 400 Energy consumption monitor from Brultech Research
Oxygen usage	O_2 flow rate to O_3 generator	Calibrated O_2 flow meter	Meter to be provided by O_2 supplier
Consumable process chemicals / additives	Feed rates	Varies with technique of feeding	Identify and specify measurement in test/QA plan
Makeup water usage	Water flow rate to APCT, by volume	Water flow meter	Orifice plate, magnetic flow meter, manual volumetic measurement
Heat recovery	Energy recovered	Energy balance	Compute from flow rates and enthalpies of heat recovery fluids
Pressure drop across APCT	Pressure difference	Differential pressure gauge or two pressure gauges	
Test Conditions Documentation			
Fuel type			Identify in test/QA plan
Reaction zone temperature	Gas temperature	Thermocouple at ozone injection point	Use a type K or J thermocouple: important parameter to verify performance.
Reactor volume (may be proprietary)	Volume in which NOx conversion reaction occurs	Calculate from dimensions given in blueprints or on-site measurements	Determine on-site: active volume to be defined in test/QA plan.
Flow rate to reactor	Flue gas volumetric flow rate to reactor.	Installed gas flow meter, EPA Methods 1- 4 or 19 (40 CFR 60 App. A)	Usually an important test condition
Combustion air to fuel ratio	Fuel flow rate	Flow meter	Orifice plate, positive displacement, or Coriolis meter
	Air flow rate	Combustion air flow meter	Orifice plate, pitot tube, or venturi tube
Percent of operating unit's rated capacity	Output computer from steam flow rate and enthalpy	Flow meter as appropriate and steam properties	Compare to manufacturer's capacity rating or experience without control technology
	Electrical power	Electrical meter	

(continued)

Table 2. (continued)

Factors to be Verified	Parameter to be Measured	Measurement Method	Comments
Test Conditions Documentation (continued)			
Ozone injection rate = O_2 (mass supply rate)* fraction O_3	O_3 fraction supplied to reaction	UV O_3 analyzer at generator discharge	Analyzer provided by vendor
	O_2 mass supply rate	Calibrated O_2 flow meter, convert volume to known conditions, then flow rate to mass supply rate.	This parameter is held constant while power to the generator is varied.
Scrubber liquid-to-gas ratio	Water flow rate to scrubber	Water flow meter	Orifice plate, magnetic, vortex shedding, or Coriolis meter
	Gas flow rate to scrubber	Installed gas flow meter, EPA Methods 1-4 or 19	Use the same flow rate measured for the reaction zone
Scrubber exit temperature	Gas temperature	Thermocouple at scrubber outlet	Use a K or J thermocouple: indicative of scrubber operation and adequate water flow
Ambient conditions	Ambient air temperature	ASTM E337-84(1996)e1: dry bulb	Measure all ambient conditions concurrently
	Ambient air pressure	ASTM D3631-95: aneroid barometer	
	Ambient air humidity	ASTM E337-84(1996)e1: psychrometer	

6.0 REPORTING AND DOCUMENTATION

This section will describe the procedures for reporting data in the Verification Test Report and the verification statement. The specifics of what data must be included and the format in which the data must be included are addressed in this section (e.g., QA/QC summary forms, raw data collected, photographs / slides / video tapes). The verification test report is expected to be about 50-70 pages in length and will include the verification statement as an addendum at the front of the report. The verification statement is a two- to five-page summary of the verification results. A preliminary draft is attached as Appendix D. The Verification Test Report, including the draft verification statement, will be prepared by the testing organization. Both will be reviewed by the APCT program before being submitted to EPA for review and approval as specified in the ETV QMP. The verification statement is approved by the APCT program as well as EPA.

6.1 Reports

The testing organization will prepare a Verification Test Report that thoroughly describes and documents the verification testing that was conducted and the results of that testing. The test report shall include the following topics:

- Verification statement
- Introduction
- Description and identification of product tested
- Procedures and methods used in testing
- Statement of operating range over which the test was conducted
- Summary and discussion of results
  - Support verification statement
  - Explain and document necessary deviations from test plan
  - Discussion of QA and QA statement
- Conclusions and recommendations
- References
- Appendices
  - QA/QC activities and results
  - Raw test data
  - Equipment calibration results

The test/QA plan must include example tables of how the data will be summarized and reported. The measurement data are to be presented in a format that allows a reviewer to easily determine whether the testing has met the data quality objectives.

The verification statement will include the following:

- APCT manufacturer/vendor information
- APCT vendor claim of performance
- Summary of verification test program
- Results of the verification test

- Any limitations of the verification results.
- Brief QA statement

Review and approval of the draft verification report and statement are as described in Section 3.0. A draft verification statement is attached as Appendix D.

6.2 Data Reduction

Data from measurements made as part of the verification test will be reported in the following units:

- The units stipulated in the method followed,
- SI units, or
- English units.

The NOx emission rate from the APCT verification test will be reported in

- Parts per million by volume (ppmv),
- Pounds per million Btu,
- ppmv corrected to a standard percent oxygen (e.g., 3% O_2 for a boiler, 7% O_2 for an incinerator, and 15% O_2 for a gas turbine), and
- Pounds per hour (lb/hr) as NO_2.

A unit conversion table from British Engineering Units to SI units will be provided. The NOx removal efficiency will be determined from the inlet NOx mass rate and the outlet NOx mass emission rate according to the following equation:

Removal efficiency, % = 100(inlet NOx, lb/hr - outlet NOx, lb/hr)/ inlet NOx, lb/hr.

6.3 Statistical Analysis of Verification Data

This section describes the statistical analysis of verification data using a physically reasonable hypothetical data set as mentioned in Section 5.1.5. This data set is for two replicates of the factorial design and is shown in Table 3. The values in Table 3 are those measured (hypothetically) after setting up the NOx control technology and combustion source to operate within the performance capability range specified by the manufacturer/vendor -- inlet NOx HI/LO of 300/55 ppmv, temperature HI/LO of 310/290°F, and flow rate HI/LO of 30,000/20,000 cfm. Note that the actual HI-LO values of the operating parameters in Table 3 are not identical to these targets. This occurs because the hypothetical test/QA plan targets will be those claimed by the manufacturer/vendor, while the values actually achieved in the field may be

Table 3. Hypothetical Data Set No. 1

Run Number	IN NOx, ppmv	TEMP, °F	FLOW, cfm	OUT NOx, ppmv
1	55.1 (LO)	285 (LO)	21,000 (LO)	1.22
2	54.7 (LO)	290 (LO)	29,000 (HI)	1.32
3	53.8 (LO)	320 (HI)	20,000 (LO)	1.11
4	55.3 (LO)	325(HI)	29,500 (HI)	1.26
5	287 (HI)	283 (LO)	20,500 (LO)	8.70
6	290 (HI)	287 (LO)	30,000 (HI)	10.2
7	292 (HI)	303 (HI)	20,000 (LO)	9.10
8	292 (HI)	306 (HI)	28,500 (HI)	9.70
9	52.8 (LO)	289 (LO)	20,400 (LO)	1.12
10	51.6 (LO)	291 (LO)	30,100 (HI)	0.98
11	53.1 (LO)	312 (HI)	20,800 (LO)	1.21
12	52.5 (LO)	315 (HI)	29,600 (HI)	1.26
13	291 (HI)	290 (LO)	20,200 (LO)	7.80
14	294 (HI)	292 (LO)	30,200 (HI)	9.20
15	289 (HI)	306 (HI)	21,100 (LO)	8.10
16	290 (HI)	309 (HI)	31,000 (HI)	9.50
Mean HI	290.5	312	29,738	
Mean LO	53.6	288	20,500	

slightly different. This sort of variability is to be expected in field tests. Some parameters can be closely controlled. Others cannot. The verification range is the range actually tested, not the range specified in the test/QA plan.

The first step in the analysis is to perform a three-factor analysis of variance on these data. The dependent variable or response is the outlet NOx concentration (OUT NOx) and the three factors are the inlet NOx concentration (IN NOx), the temperature in the reaction chamber where ozone is injected (Temp), and the gas flow at the inlet to the reaction chamber (FLOW). The example calculations were performed using SYSTAT statistical software.

The analysis of variance included all three main effects as well as their interactions; e.g., the interaction of IN NOx and TEMP. This analysis calculates a P-value that indicates the statistical significance of each parameter or combination of parameters. The lower the P-value the greater the statistical significance, and a P-value below 0.05 indicates that the probability that the tested interaction is due to random chance is 5% or less. Stated positively, a P-value of 0.05 indicates that there is a 95% chance that the observed interaction is a real effect and not due to chance variation in the measurements. For the hypothetical data set, this analysis showed that

the parameters IN NOx and FLOW and their interaction (IN NOx * FLOW) were statistically significant at the 95% level, with P-values of 0.00, 0.019, and 0.025, respectively. IN NOx was clearly the most significant.

The next step in the statistical analysis was to repeat the analysis of variance including only the significant factors: IN NOx, FLOW, and their interaction. This step confirmed that all the factors remain significant, with P-values below 0.05. It also showed that only the IN NOx parameter was significant at the 99% level (P-value below 0.01). At this point a decision must be made whether a significance below 99% is important in reporting the results; i.e., should the effects of FLOW and IN NOx * FLOW be included in the verification results. Otherwise, the verification performance results would be reported in terms of only IN NOx.

For purposes of this example, it was assumed that only the effect of IN NOx was significant enough to be of interest. Variation in the performance results due to the parameter FLOW or the interaction will not be accounted for separately, but as part of the variation related to the parameter IN NOx. Two approaches can be used for the final analysis. One is to fit a model with IN NOx as the only parameter. This result is shown in Table 4. The estimated performance results are presented separately for the low and high IN NOx levels. Confidence intervals for the OUT NOx level can be calculated by taking the mean for each IN NOx level and

Table 4. IN NOx Model

Parameter or Interaction - Level	OUT NOx Least Square Mean, ppmv	Standard Error, ppmv
IN NOx - Low	1.185	0.204
IN NOx - High	9.038	0.240

adding and subtracting the t-value for 14 degrees of freedom and a 95% confidence interval times the standard error indicated in the table. The t-value for this example is 2.145; it can be found in standard statistical texts. The verification claim in this case would be that, for temperatures between 288 and 312 °F and flow rates between 20,500 and 29,740 cfm, the outlet NOx concentration was 1.185 ± 0.438 ppmv at an inlet NOx concentration of 54 ppmv and 9.038 ± 0.515 ppmv at an inlet NOx concentration of 290 ppmv. These results meet the DQOs stated in Section 2.3.

The second approach to estimating the performance of the control device is to perform a regression of OUT NOx on IN NOx. The result is an equation of the form

$$\text{OUT NOx} = a + b\,(\text{IN NOx})$$

that can be used to predict the OUT NOx as a function of IN NOx. For this example, the estimated value of a, the intercept, is -0.593 ppmv while that of b, the slope, is 0.033. Thus, the predicted equation is

$$\text{OUT NOx} = -0.593 + 0.033\ (\text{IN NOx})$$

This linear equation would be applicable over the tested ranges of temperature, flow rate, and inlet NOx values. Outside these ranges it might be useful, but such use has not been verified.

In some cases, the difference in OUT NOx values for the low and high IN NOx levels may be too small to be of practical importance. For example, if the OUT NOx differed by only 1 ppmv between the low and high IN NOx levels, then one would not likely make a distinction in performance based on the IN NOx level as in the example above. For such a case, the overall mean OUT NOx would be calculated and reported along with the appropriate confidence interval.

7.0 DISSEMINATION OF VERIFICATION REPORTS AND STATEMENTS

After a product has been tested and the draft report and verification statement received from the testing organization, the APCT program will send a draft of both to the manufacturer/ vendor for review prior to submission to EPA and release to the public. This gives the manufacturer/vendor an opportunity to review the results, test methodology, and report terminology while the drafts remain working documents and are not publically accessible. The manufacturer/vendor may submit comments and revisions on the draft statement and report to the APCT program. The APCT program will consider these comments and may suggest revisions of its own. Revisions will be made by the testing organization. The revised verification report and verification statement will be returned to the manufacturer/vendor for final review. Alternatives available to the manufacturer in the case of unsatisfactory performance (see Section 8.0) must be exercised at this time.

After final review by the manufacturer/vendor and review by the APCT program, the draft final verification report and statement will be submitted to EPA for review and approval. Several copies of the verification report will be provided to the manufacturer/vendor. Distribution, if desired, is at the manufacturer/vendor's discretion and responsibility. Verification statements will be posted on the ETV web site for public access without restriction. An original signed verification statement will be provided to the manufacturer/vendor of the control technology.

8.0 MANUFACTURER/VENDOR'S OPTIONS IF A TECHNOLOGY PERFORMS BELOW EXPECTATIONS

ETV is not a technology research and development program; technologies submitted for verification are to be commercial-ready and with well-understood performance. In the event that a technology fails to meet the manufacturer's expectations, the manufacturer/vendor has two alternatives. The first recourse is to simply request that a verification statement not be issued. However, verification tests that are funded partially by EPA will always be in the public domain. Verification reports will be written for publicly funded tests, and these will be available from EPA for review by the public regardless of a request not to issue a verification statement.

As a second alternative for unfortunate situations that might arise, the APCT program

will allow manufacturer/vendors to "re-purchase" the test by paying the APCT program for its full cost up to the time the decision is made to terminate and re-purchase. Exercising this option results in the verification test's being a private transaction, and no government funds will have been expended to support the work, so that the results and report become the property of the manufacturer/vendor. The full cost of a test is defined as all costs incurred by the APCT program and its subcontractors that are associated directly with the verification test. For example, site visits, test/QA plan development, the verification test, data analysis, on- and off-site management, QA review and audit, and preparation of verification reports and statements are all elements of the full cost of a verification test. These alternatives will be described in contractual documents between the APCT and manufacturer/vendors.

The manufacturer may improve the product and resubmit it under a new model identification for verification testing. Verification statements for tests of the new product will be issued as they are processed by the APCT program and EPA (except that the results for several identical tests performed in rapid succession will all be released at the same time.)

9.0 LIMITATIONS ON TESTING AND REPORTING

To avoid having multiple ETV reports for the same product and to maintain the verification testing as a cooperative effort with manufacturer/vendors, the following restrictions apply to verification testing under this protocol:

- Manufacturer/vendors may submit only their own products for testing; manufacturer/vendors may not submit control devices from other manufacturers for verification testing.
- For a given product (e.g., brand and model), APCT policy is that only one ETV verification report and statement will be issued for any single application.
- Air pollution control technology frequently performs differently in different applications. Manufacturer/vendors may request additional tests of essentially identical technology if it is being applied to pollution sources that are clearly different from those for which verifications have been obtained.

Specific NOx control technology may be tested at host industrial sites at which it has been installed. The APCT program will not identify the host site, without permission, in verification reports and statements.

10.0 REQUIREMENTS FOR TEST/QA PLAN

10.1 Quality Management

All testing organizations participating in the NOx Control Technology Program must meet the QA/QC requirements defined below and have an adequate quality system to manage the quality of work performed. Documentation and records management must be performed according to the *ETV Quality and Management Plan for the Pilot Period (1995-2000)* (ETV QMP, EPA, 1998a.) Testing organizations must also perform assessments and allow audits by

the APCT program (headed by the APCT QA Officer) and EPA corresponding to those in Section 11.

All testing organizations participating in the NOx Control Technology Program must have an ISO 9000-accredited (ISO, 1994) or ANSI E4-compliant (ANSI, 1994) quality system and an EPA- or APCT program-approved QMP. The APCT program will approve the QMP of the testing organization.

10.2 Quality Assurance (QA)

All verification testing will be done following an approved test/QA plan that meets *EPA Requirements for Quality Assurance Project Plans for Environmental Data Operations* (EPA 1998c) and Part B, Section 2.2.2 of EPA's ETV QMP (EPA, 1998a). These documents establish the requirements for test/QA plans and the common guidance document, *Guidance for Quality Assurance Project Plans* (EPA, 1998b), provides guidance on how to meet these requirements. The APCT Quality Management Plan (RTI, 1998) implements this guidance for the APCT program. The test/QA plan must describe how the methods described in Appendix A of this generic verification protocol will be implemented by the testing organization and the steps the testing organization will take to ensure acceptable data quality in the test results. Any needed standard operating procedures (SOPs) will be developed in accordance with *Guidance for the Preparation of Standard Operating Procedures (SOPs) for Quality Related Documents* (EPA, 1995.)

The testing organization must prepare a test/QA plan and submit it for approval by the APCT program. The test/QA plan must be approved before the test organization can begin verification testing.

A test/QA plan contains the following elements. If specific elements are not included, an explanation for not including them must be provided.

- Title and approval sheet;
- Table of contents, distribution list;
- Test description, test objectives;
- Identification of the critical measurements, data quality objectives (DQOs) and indicators, test schedule, and milestones;
- Organization of test team and responsibilities of members of that team;
- Documentation and records;
- Test design;
- Sampling procedures;
- Sample handling and custody;
- Analytical procedures;
- Test-specific procedures for assessing data quality indicators;
- Calibrations and frequency;
- Data acquisition and data management procedures;
- Internal systems and performance audits;
- Corrective action procedures;

- Assessment reports to EPA;
- Data reduction, data review, data validation, and data reporting procedures;
- Reporting of data quality indicators for critical measurements;
- Limitations of the data; and
- Any deviations from methods or this generic verification protocol.

10.3 Additional Requirements To Be Included in the Test/QA Plan

The test/QA plan must include a diagram and description of the extractive gaseous measurement system to be used for the testing and a list of the reference analyzers and measurement ranges to be used for quantifying the gaseous concentrations. Additional analyzers (CO and THC) in the sampling system diagram must also be included, as well as a list of the reference analyzers and measurement ranges to be used for quantifying CO and THC concentrations.

The test/QA plan must include a schematic of all sample and test locations, including the inlet and outlet to the technology sampling locations. The location of flow disturbances and the upstream and downstream distances from the sampling ports to those flow disturbances must be noted. The number of traverse points that will be sampled must be provided.

The test/QA plan must include the appropriately detailed descriptions of all measuring devices that will be used during the test. These measurements are expected to include those listed in Table 2 and any additional measurements identified as required during site visits and consideration of the test site.

The test/QA plan must explain the specific techniques to be used for monitoring process conditions appropriately for the source being tested. It must also note the techniques that will be used to estimate any other operational parameters. For example, the reaction zone volume is a design parameter that, along with flow rate, determines residence time. It may be measured on site or provided by the vendor.

11.0 ASSESSMENT AND RESPONSE

The APCT program and/or EPA will conduct assessments to determine the testing organization's compliance with its test/QA plan. The requirement to conduct assessments is specified in EPA's *Quality and Management Plan for the Pilot Period (1995 - 2000)* (EPA, 1998a), and in RTI's QMP (RTI, 1998.) EPA will assess RTI's compliance with RTI's test/QA plans. RTI will assess the compliance of other organizations with their test/QA plans. The assessments will be conducted according to *Guidance on Technical Assessments for Environmental Data Operations* (EPA, 1999.)

11.1 Assessment Types

Technical systems audit - Qualitative on-site audit of the physical setup of the test. The auditors determine the compliance of testing personnel with the test/QA plan.

Performance evaluation audit - Quantitative audit in which measurement data are independently obtained and compared with routinely obtained data to evaluate the accuracy (bias and precision) of a measurement system.

Audit of data quality - Qualitative and quantitative audit in which data and data handling are reviewed and data quality and data usability are assessed.

11.2 Assessment Frequency

Activities performed during technology verification performance operations that affect the quality of the data shall be assessed regularly, and the findings reported to management to ensure that the requirements stated in the generic verification protocols and the test/QA plans are being implemented as prescribed.

The types and minimum frequency of assessments for the ETV Program are listed in Part A Section 9.0 of EPA's *Quality and Management Plan for the Pilot Period (1995 - 2000)*. Tests conducted during the APCT program will have at a minimum the following types and numbers of assessments:

1. Technical systems audits – self-assessments for each test as provided for in the test/QA plan and independent assessments, twice for the APCT program.
2. Performance evaluation audits – self-assessments, as applicable, for each test as provided in the test/QA plan and independent assessments, as applicable for each different technology verified by the APCT program.
3. Audits of data quality – self-assessments of at least 10% of all the verification data; and independent assessment, as applicable for the APCT program.

The independent assessments of tests conducted by RTI will be performed by EPA. The independent assessments of other organizations will be by RTI.

11.3 Response to Assessment

Appropriate corrective actions shall be taken and their adequacy verified and documented in response to the findings of the assessments. Data found to have been taken from non-conforming technology shall be evaluated to determine its impact on the quality of the data. The impact and the action taken shall be documented. Assessments are conducted according to procedures contained in the APCT QMP. Findings are provided in audit reports. Responses to adverse findings are required within 10 working days of receiving the audit report. Followup by the auditors and documentation of responses are required.

12.0 SAFETY MEASURES

12.1 Safety Responsibilities

The test company's field team leader is responsible for ensuring compliance with plant

entry, health, and safety requirements. Although the field team leader is responsible, each individual staff member is expected to follow the requirements and identify personnel who deviate from them.

12.2 Safety Program

The test company must maintain a comprehensive safety program that all field personnel must read and follow. In addition, field personnel are expected to familiarize themselves with the site safety practices. If required, field personnel will attend a safety orientation with the plant safety officer. Before or on the first day onsite, the test company's Field Team Leader will fill out an Emergency Response Procedure form, discuss it with test team members, and post it at a place or places accessible to all test team work stations. The form will include as a minimum:

- Procedures for obtaining emergency medical assistance,
- Location of first aid station(s), and
- Location and directions to local hospital(s).

12.3 Safety Requirements

All test personnel will adhere to the following general safety requirements:

- Confine themselves to authorized areas only,
- Wear protective glasses or goggles and headgear at all times where designated,
- Wear steel-toed boots/shoes where designated,
- Wear hearing protection at all locations where designated, and
- Wear other personal protective equipment as required and/or specified in the test/QA plan.

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APPENDIX A: METHODS AND PROCEDURES

A1.0 Performance Factors Measurements

The sampling and analytical procedures for verifying the vendor's performance claims include determining NOx concentration at the technology outlet and NOx emission rates at the inlet and outlet to the control device. The following measurements will be made according to the noted test method:

- NOx concentration - EPA Method 7E (40 CFR 60 App. A)
- Flue gas flow rate - EPA Methods 1, 2, 3, 3A, or 3B, and 4; (40 CFR 60 App. A)

Table A-1 lists the acceptable calibration gas concentrations for the instrumental methods 3A and 7E. EPA protocol gas will be used to calibrate the monitors.

Table A-1. Calibration Gas Concentrations

Calibration Point	O_2	CO_2	NOx
Zero	0 - 0.06%	0 - 0.05 %	0 - 0.25% of span
Mid-level	10 - 15 %	8 - 12 %	40 - 60 % of span
High-level	20 - 25 %	16 - 20 %	80 - 100 % of span

A gas dilution system (e.g., Environics Model 2020) can be used in accordance with 40 CFR Part 51, Method 205 to get the required gas concentrations from a single, high concentration EPA protocol gas.

The exhaust gas moisture, O_2, and CO_2 will be used to calculate the exhaust gas molecular weight. The exhaust gas molecular weight and exhaust gas velocity (from Methods 1 and 2) will be used to calculate the exhaust gas volumetric flow rate so that the NOx concentration can be related to mass emission rate (lb/hr). The following equation will be used to calculate the NOx (as nitrogen dioxide) mass emission rate:

$$\text{NOx (lb/hr)} = \text{NOx (ppm)} * 46 * Q_{std} * 60 / 10^6 / 385.6$$

where:

NOx (ppm) = corrected NOx concentration (C_{gas}),
46 = nitrogen dioxide molecular weight, lb/mole, per Method 7E,
Q_{std} = volumetric flow rate corrected to dry standard conditions (dscfm),
60 = minutes per hour,
10^6 = ppmv conversion, and
385.6 = molar volume, ft^3/mole, at standard temperature and pressure.

Before the verification test runs, a test will be performed at each sampling location to verify the absence of cyclonic flow. The technique described in Section 2.4 of Method 1 will be followed to verify the absence of cyclonic flow. If the average of the yaw angles is $\leq 20^o$, the sampling location is acceptable for velocity measurements. If cyclonic flow is present, either flow-straightening vanes will be installed or a different location will be used for the velocity measurements. If an acceptable location cannot be found, the sampling site shall be deemed unacceptable or Method 19 procedures will be followed to determine the NOx emission rate. Method 19 may also be used as an alternative to measuring exhaust gas volumetric flow rate.

If Method 19 procedures are chosen, the dry, oxygen-based F-factor (Section 2.1 of Method 19) technique will be used. The NOx concentration (from Method 7E) will be converted to the units of pounds per standard cubic foot (lb/scf) by multiplying the NOx ppmv value by 1.194×10^{-7}. The F-factor must be in units of scf/million Btu. The standard, dry basis F-factor values (F_d), presented in Table 19-1 of Method 19, will be used. If a site specific fuel factor is determined, that value will be used if the supporting laboratory data are provided. The following equation (Eq. 19-1 from Method 19) will be used to calculate NOx emission rates normalized to heat input:

$$E = C_d * F_d * [20.9 / (20.9 - \%O_{2d})]$$

where:
E= NOx emission rate in lb/million Btu
C_d = NOx concentration in lb/dscf
F_d = dry F-factor in dscf/million Btu
$\%O_{2d}$ = dry O_2 concentration in percent.

A2.0 Associated Impacts Measurements

The procedures for measuring the potential environmental impacts (i.e., side effects) associated with the operation of the control technology are presented in this section. These procedures include standard practices and EPA reference methods.

A2.1 Stack Gas Ozone Concentration

NIOSH Method 154 will be used to measure ozone concentration in the stack gas. This method uses a 1% potassium iodide in 1.0 N sodium hydroxide absorbing solution in a midget impinger sampling train. Sample duration will be 60 minutes per test run at a sampling rate of 1 L/min. Samples are analyzed colorimetrically with a UV-VIS spectrophotometer at 352 nm.

As an alternative to the wet chemistry method noted above, an ultraviolet photometric analyzer may be used to measure the ozone slip. This instrument will be operated by the technology vendor/operator. The operator must provide suitable QC information for this instrument.

A2.2 Stack Gas CO and THC Concentration

CO and THC measurements will be made using the same sampling system used for NOx

testing. EPA Method 10 will be followed for CO and Method 25A will be followed for THC. The only modification will be the use of a slipstream (by installing a tee) before the moisture removal system to provide a hot sample gas to the THC monitor. The slipstream sample will be maintained at a temperature above the moisture dew point to prevent condensation in the sample line.

Table A-2 lists the acceptable calibration gas concentrations for Methods 10 and 25A. EPA protocol gas will be used to calibrate the monitors.

Table A-2. Methods 10 and 25A Calibration Gas Concentrations

Calibration Point	CO	THC
Zero	purified N_2	purified air
Low-level	30 % of span	25 - 35 % of span
Mid-level	60 % of span	45 - 55 % of span
High-level	90 % of span	80 - 90 % of span

A2.3 Methane and Ethane

The concentration of methane and ethane will be determined using the EPA Method 18 integrated bag sampling technique. The results of the Method 18 samples will be subtracted from the Method 25A results to estimate VOC concentration.

A2.4 Stack Gas SO_x Concentration

The concentration of SO_x will be determined using either (1) Method 6 or 6C for SO_2 or (2) Method 8 for sulfuric acid mist (including SO_3) and SO_2. Method 6 will use 3% H_2O_2 absorbing solution in a midget impinger train. Sampling will be conducted at a rate of 1 L/min with the total sample volume measured by a dry gas meter. Analysis will be by barium-thorin titration. Instrumental Method 6C will use the same sampling system as the other instrumental sampling methods. The SO_2 analyzer will use UV absorption or fluorescence. The calibration gas levels listed for NOx in Table A-1 will also be used for SO_2. Method 8 will use a Method 5 sampling train, except that an unheated filter will be placed between the first and second impingers and isokinetic sampling procedures will be used. The impingers will contain the following: first impinger - 80% isopropanol, second and third impingers - 3% H_2O_2.

A2.5 Stack Gas Cl_2 Concentration

The concentration of Cl_2 will be determined using Method 26A. Method 26A uses a Method 5 sampling train, except that five impingers are used and isokinetic sampling procedures are used. The first and second impingers will contain 0.1N H_2SO_4, the third and fourth impingers will contain 0.1 N NaOH, and the last impinger will contain silica gel.

A2.6 Acids in Wastewater

The concentration of acids in the wastewater stream will be measured with a pH meter according to ASTM E70-90 - Standard Test Method for pH of Aqueous Solutions With the Glass Electrode. The pH metering station will either be an in-line or off-line laboratory measurement. The in-line station will use either a built-in electrode assembly or a flow-through electrode assembly. For an off-line station, samples will be withdrawn at a sample vent and taken to the pH meter.

If the in-line metering station is used, the measurements will be recorded by the process' data acquisition system on a continuous basis. If the pH is measured off-line, one sample will be collected and measured for each test run at a time specified in the test/QA plan.

A2.7 Wastewater Flow Rate

To measure the increased impact of wastewater generated by the control device, the wastewater flow rate from the device will be measured. See the discussion on fluid flow measurements (Section A5) for reference to water flow meters.

A2.8 Total Dissolved Solids

EPA Method 160.3 will be used to determine the total dissolved solids in the wastewater discharge from the scrubber. This method measures the amount of solids in the wastewater by passing the sample through a glass fiber filter. At least three samples of the wastewater discharge will be collected. Samples will be stored in refrigerated conditions, and analysis will be done within 7 days of sample collection.

A2.9 Other Wastewater Measurements

Depending on the process, other wastewater measurements may be appropriate to include in the test/QA plan. If required, those measurements will be conducted following EPA standards or other published methods when available.

A3.0 Associated Resource Usage Measurements

The procedures for measuring the potential logistical, human, and economic impacts (i.e., side effects) associated with the operation of the control technology are presented in this section. These procedures include standard practices for such measurements, where applicable.

A3.1 Energy Consumption of Ozone Generator

Energy consumption for the ozone generator will be measured according to ASTM E929-83 (1988) - Standard Test Method for Measuring Electrical Energy Requirements of Processing Equipment. An energy consumption monitor (e.g., ECM 1200 or 400 from Brultech) or similar device may be used, calibrated as suggested by the instrument manufacturer.

A3.2 Energy Consumption of Fan

Energy consumption for the fan will be measured according to ASTM E929-83 (1988) - Standard Test Method for Measuring Electrical Energy Requirements of Processing Equipment. An energy consumption monitor (e.g., ECM 1200 or 400 from Brultech) or similar device may be used, calibrated as suggested by the instrument manufacturer.

A3.3 Oxygen Usage

Determination of the amount of oxygen used to produce the ozone may be done with a flow meter calibrated specifically for O_2. The O_2 flow rate in units of cubic feet per minute will be converted to pounds per hour. The flow meter will be provided by the technology vendor. The vendor must provide information on the accuracy of this meter and required QA information regarding operation and calibration.

A3.4 Alkali

Measurement of the alkali feed rate to the scrubber will depend on the feeding technique. The methodology to be used will be specified in the test/QA plan for the specific test planned.

A3.5 Heat Recovery

The heat recovered by the technology that is available to the host site for usage will be determined based on a simple energy balance. The heat exchanger's inlet and outlet gas temperature and mass flow rate will be measured and used for the energy balance.

A3.6 Pressure Drop Across Technology

The pressure drop across the technology will be measured with a differential pressure device or up- and downstream pressure measurements. This device and data will be provided by the vendor.

A4.0 Test Conditions Measurements

The procedures for measuring or documenting the conditions under which the technology being verified was operating during the verification test program are presented in this section.

A4.1 Reaction Zone Gas Temperature

The gas temperature at the reaction zone is an important operating parameter. A type K or J thermocouple will be used to measure the gas temperature. The thermocouple and temperature measurement value will be provided by the technology vendor. An assessment of the accuracy of the measured value must be provided.

A4.2 Reaction Zone Residence Time

The reaction zone residence time, if determined, is the actual reactor volume divided by the volumetric flow rate. Reactor volume will be obtained by on-site measurements or from blueprints. During the steady-state test runs, the gas volumetric flow rate at the inlet to the reaction chamber will be measured by an installed air flow meter or manually with EPA Methods 1 through 4 (Method 19 may be substituted). See the discussion below on fluid flow measurement (Section A5) for reference to possible flow meters for this application. If manual EPA methods are used, the measurement location must meet Method 1 minimum criteria.

A4.3 Fuel Flow Rate

The fuel flow rate into the combustion chamber will be measured for use in calculating the combustion air-to-fuel ratio. See Section A5 of this protocol for reference to fluid flow meters.

A4.4 Combustion Air Flow Rate

The air flow rate into the combustion chamber will be measured for use in calculating the combustion-air-to-fuel ratio. See Section A5 below on fluid flow measurement for reference to possible air flow rate meters.

A4.5 Steam Flow Rate

Steam flow rate will be measured for use in determining the unit's operating capacity during the verification test. See Section A5 below on fluid flow measurement for reference to possible steam flow meters.

A4.6 Electrical Generation

One possible means to determine the host unit's operating rate during the verification test is to record the electrical power production from the electrical generator.

A4.7 Ozone Weight Percent

The O_3 weight percent will be used with the O_2 supply rate to the ozone generator to determine the ozone injection rate. The O_3 weight percent will be determined by a UV O_3 analyzer provided by the technology vendor. The O_3 analyzer will provide a signal output of weight percent of O_3. The technology vendor will be responsible for documenting the accuracy of the O_3 measurement.

A4.8 Oxygen Supply Rate

The O_2 supply rate to the O_3 generator will be measured with a flow meter specifically calibrated for O_2. The volumetric output of the device will be converted to lb/hr. The O_2 flow meter will be provided by the technology vendor as part of the O_3 generation equipment. The

product of O_2 supply rate and O_3 weight percentage will give the O_3 injection rate.

A4.9 Water Flow Rate to Scrubber

Water flow rate to the scrubber will be measured for use in determining the liquid-to-gas (L/G) ratio. See the discussion below (Section A5) on fluid flow measurement for reference to possible water flow meters.

A4.10 Gas Flow Rate to Scrubber

Gas flow rate through the scrubber will be used to calculate the L/G ratio. The same measurements and value calculated for gas volumetric flow rate in the reaction zone will be used in the scrubber L/G ratio.

A4.11 Scrubber Exit Gas Temperature

As an indicator of scrubber operation and adequate water flow, the scrubber exit gas temperature will be measured. A type K or J thermocouple will be used to measure the gas temperature at the exit of the scrubber.

A4.12 Ambient Humidity and Temperature

A sling psychrometer will be used for obtaining the wet and dry bulb temperatures that will be used to calculate ambient humidity (from a psychrometric chart) according to ASTM E337-84(1996)e1 - Standard Test Method for Measuring Humidity with a Psychrometer. The dry bulb temperature will be reported as the ambient temperature.

A4.13 Ambient Pressure Measurement

Ambient pressure will be measured with a mechanical pressure device (aneroid barometer) in accordance with ASTM D3631-95 - Standard Test Method for Measuring Surface Atmospheric Pressure.

A5.0 Fluid Flow Measurements

Several of the test condition parameters involve measurement of fluid (air and liquid) flow rate. Several techniques are available for measuring fluid flow rate.

A5.1 Orifice Plate for Fluid Flow Rate

Differential pressure flow meters (e.g., orifice plates and venturi meters) represent one of the most commonly used flow meter technologies in industrial applications. The orifice plate presents a constriction to the stream of fluid and causes a pressure drop across the plate. The pressure drop, measured by a differential pressure gauge, is read across two pressure taps, one upstream and one downstream of the plate. The pressure drop is proportional to the fluid flow rate through the pipe. Orifice plates and venturi meters require calibration and knowledge of

fluid properties (e.g., density at pressure and temperature of fluid) to convert the measured pressure drop to fluid flow rate.

A5.2 Magnetic Flow Meters

Magnetic flow meters are effective for monitoring the flow rate of liquids that present difficult handling problems, and this flow meter is likely the one that will be used to measure a liquid oxidizing/reducing agent injection rate. Magnetic flow meters are not used for measuring the flow rates of gaseous compounds. In a magnetic flow meter, a voltage induced in the fluid flowing in the pipe, moving in a magnetic field, is proportional to the velocity of the fluid.

A5.3 Positive Displacement Flow Meters

Positive displacement flow meters can be used to measure the flow rate of both liquids and gases. This device will likely be used to measure the volumetric flow rate of a liquid fuel such as fuel oil. Positive displacement type flow meters repeatedly entrap a known quantity of fluid as it passes through the meter. The number of times the fluid is entrapped is counted; therefore, the quantity of fluid passed through the flow meter is obtained. The flow rate is the difference between a final reading and an initial volume reading divided by the time between readings. Positive displacement meters usually have a set of rolling numbers (similar to an odometer) for recording the volume.

A5.4 Turbine Flow Meters

Turbine flow meters can be used to measure the flow rate of both liquids and gases. A turbine flow meter consists of a rotating device (i.e., rotor) positioned in the fluid stream such that the rotational velocity of the rotor is proportional to the fluid velocity.

A5.5 Vortex Shedding Flow Meters

In a vortex shedding meter, a vortex is generated by a blunt, typically flat-faced, body placed perpendicular to the flowing fluid. The vortex generating body causes a separation in the fluid that forms a shear layer. At a specific distance downstream, the fluid in the shear layer breaks into well-formed vortices. The vortices are formed and shed with a frequency that is proportional to the fluid velocity. Vortex shedding flow meters are applicable to low viscosity liquids and pressurized gases with a density high enough to operate the flow meter.

A5.6 Coriolis Mass Flow Meters

A Coriolis mass flow meter consists of one or two U-shaped tubes that deflect or vibrate as the fluid flows through the tubes. The operating principle is based on conservation of angular momentum. As fluid enters the U-shaped tube(s), it is forced to take on the vertical movement of the vibrating tube. When the tube is moving upward, the fluid flowing into the meter resists being forced up by pushing down on the tube. Having been forced upward, the fluid flowing out of the meter resists having its vertical motion decreased by pushing up on the tube. The two opposing forces on the tube cause it to twist. The amount of twist is directly proportional to the

mass rate of the fluid flowing through the tube(s). This flow meter is generally limited to liquid flow rate applications.

A6.0 Temperature Measurements

Temperature measurement can be accomplished using several types of sensing mechanisms. For this verification test, temperature measurements will be made by:

- Thermocouple,
- IR thermometer, and
- Fluid expansion device.

A6.1 Temperature Measurement by Thermocouple

A thermocouple is a self-powered temperature transducer that operates because wires of dissimilar conductive materials generate current when joined in a loop if the two junctions are at different temperatures. Opening the loop at one junction gives an electrical potential difference across the two dissimilar material wires. Practically, two thermocouple junctions are wired in series, and one of the junctions is held at a fixed known temperature, frequently the temperature of melting ice. The other junction is the measurement thermocouple, and the resulting open circuit voltage is proportional to temperature. Types J (iron - copper/nickel) and K (chromium/nickel - copper) thermocouples will be used.

A6.2 Temperature Measurement by IR Thermometer

An infrared (IR) thermometer measures the IR energy emitted by an object and converts the measurement to the corresponding temperature. The principle is based on the theoretical blackbody radiation. However, since real objects (gray bodies) emit only a portion of the IR energy that a blackbody would emit, a compensation is made for the emissivity of the object. Since IR thermometers respond to the radiation emitted by an object, they operate remotely without contacting the object, and are therefore ideal for measuring flame temperatures.

A6.3 Temperature Measurement by Fluid Expansion Device

A fluid expansion device (e.g., red-alcohol-in-glass thermometer) measures temperature as a function of the thermal expansion of the organic liquid over a calibrated scale. An alcohol thermometer will be used to measure wet bulb and dry bulb temperatures from a sling psychrometer for ambient humidity.

APPENDIX B: QUALITY CONTROL (QC)

This Appendix specifies QC procedures for the measurement methods that will ensure data quality and integrity. This Appendix addresses: QA responsibilities; data quality indicators, including data representativeness, completeness, accuracy, precision, and statistical uncertainty; QC for technology operation, including methods to be used and frequency of QC checks (i.e., daily analyzer linearity, sampling system bias, analyzer drift); sample quality (i.e., specified number of samples to be analyzed); procedures for data reduction, validation, and reporting; and the frequency, format, and content of reports.

B1.0 Specific QC Procedures for Instrumental Test Methods

B1.1 Interference Test

For the interference test, the gases listed in Table B-1 must be injected into each analyzer. For acceptable analyzer performance, the sum of the interference responses to all of the interference gases must be ≤2 % of the analyzer span value.

Table B-1. Analyzer Interference Test Gas Concentrations

CO	SO_2	CO_2	O_2
500±50 ppm	200±20 ppm	10±1 %	20.9±1 %

B1.2 Daily Calibration Error Checks

Daily analyzer calibration error checks will be conducted before the start of each day's testing. The calibration error check will be conducted (after final calibration adjustments are made) by separately injecting each of the three calibration gases (zero, mid-, and high-level) directly into each analyzer and recording the response. The calibration gas concentrations to be used are presented in Appendix A, Table A-1. The reference calibration gases to be used in this test program will be certified following the EPA protocol gas analysis procedure. Copies of the calibration gas certification will be available on-site. An analyzer's calibration error at each calibration point will be ≤2 % of the analyzer span value. If the calibration error is greater than 2 %, the analyzer will be repaired or replaced and recalibrated to an acceptable calibration error limit before proceeding.

B1.3 System Bias and Drift Checks

Zero and upscale calibration checks will be performed both before and after each test run to quantify reference measurement system calibration drift and sampling system bias. Upscale will be either the mid- or high-level gas, whichever most closely approximates the sample gas concentration level. During these checks the calibration gases will be introduced into the sampling system at the probe outlet so that they are sampled and analyzed in the same manner as the sample gas. Drift is defined as the difference between the pre- and post-test run system

calibration check responses. Sampling system bias is the difference between the system calibration check response and the initial calibration error response (direct analyzer calibration) at the zero and upscale calibration gas levels. If acceptable bias check results are obtained (system bias ≤5 % of the analyzer span value) but the zero or upscale drift result exceeds the drift limit (3 % of the analyzer span value), the test run result will be considered valid; however, the analyzer calibration error and bias check procedures will be repeated before conducting the next test run. If the post-test zero or upscale system bias check result exceeds the specification, the test run will be considered invalid.

B1.4 System Response Time Check

To determine the response time, the zero gas will be injected into the sampling system at the calibration valve on the probe. When all the analyzers' readings are stable, the valve will be turned to sample effluent. When a stable reading is obtained, the upscale response time will be determined as the time required for the recording device (computer readout) to record a 95 % step change from the zero reading to the stable effluent concentration. Then the high-level calibration gas for each monitor will be injected to the sampling system at the calibration valve on the probe. When all the analyzers are stable, the valve will be turned to sample effluent. When a stable reading is obtained, the downscale response time will be determined as the time required for the recording device (computer readout) to record a 95 % step change from the calibration gas reading to the stable effluent concentration. This procedure will be repeated until three upscale and three downscale response times are completed. The longest of all the upscale and downscale response times will be reported as the system response time.

At the start of each test run, readings will only be taken after the system has been sampling at the sample point for more than twice the system response time.

B1.5 EPA Method 25A System Response Time Check

For EPA Method 25A, only an upscale response time test will be done. To determine the upscale response time, the zero gas will be injected into the sampling system at the calibration valve on the probe. Then, the high-level calibration gas will be injected into the sampling system. The upscale response time will be determined as the time required for the recording device (computer readout) to reach 95 % of the high-level calibration gas reading. This procedure will be repeated three times, and the average will be reported as the response time.

B1.6 QC Requirements Specific to EPA Method 7E

The NOx analyzer's analytical technique must use chemiluminescence. The calibration gases for the NOx monitoring system will be NO in N_2, and ambient air may be used for the zero gas.

1. Converter Efficiency Test
   - For an acceptable converter, the 1-minute average response at the end of 30 minutes shall not decrease more than 2.0 % of the highest peak 1-minute value.

- An alternative procedure, using an EPA protocol cylinder of NO_2 in N_2 instead of the bag procedure, for doing the converter efficiency test may be used.

2. NOx Analyzer Span
   - The NOx analyzer's span shall be such that the NOx concentration equivalent to the emission standard shall not be less than 30 % of the upper measurement limit of the instrument.
   - If any measured gas concentration exceeds the analyzer's span, the run will be invalid.

B1.7 QC Requirements Specific to EPA Method 3A

The calibration gases will be CO_2 in N_2 or air and O_2 in N_2.

1. O_2 and CO_2 Analyzers' Span
   - The analyzer span for each monitor shall be such that the average O_2 or CO_2 concentration is not less than 20 % of the span value.
   - Typically, the O_2 span value is 25 %, and the CO_2 span value is 20 %.
2. Comparison to Orsat Analysis
   - O_2 and CO_2 instrumental measurements will be validated for at least one test run using a gas sample collected in a bag and analyzed for O_2 and CO_2 by an Orsat analyzer.
   - Any difference between the Orsat analysis and Method 3A greater than 0.5 % will be investigated and corrective action taken as appropriate. If the difference is found to be due to a problem with the instrumental sampling system, the system or analyzer will be repaired before continuing. If the analyzer cannot be repaired, O_2 and/or CO_2 values will be obtained using Method 3 procedures (i.e., the Orsat).
4. Comparison to Fuel Factor, F_o
   - The measured O_2 and CO_2 will be used to calculate a fuel factor, F_o, using

$$F_o = (20.9 - \%O_2) / \%CO_2$$

   - The calculated F_o will be compared to the range of expected F_o values based on the fuel combusted, as found in Method 3B, section 3.4.1.2.

B1.8 QC Requirements Specific to EPA Method 10

1. CO Analyzer Span
   - According to EPA Method 10, the CO analyzer's span is to be set at 1,000 ppm. However, for this test program, the CO analyzer's span will be such that the majority of the 1-minute CO concentration averages are between 20 and 80 % of the selected span value.
   - If any measured gas concentration exceeds the analyzer's span, the CO data from the run will be invalid.

B1.9 QC Requirements Specific to EPA Method 25A

1. Calibration Error and Drift Checks
   - An initial calibration error check will be done within 2 hours of the start of a test run.
   - The zero and high-level calibration gases will be injected into the sampling system at the probe outlet and the analyzer set to read the appropriate value.
   - Then, the low- and mid-level gases will be sequentially injected into the sampling system at the probe outlet.
   - The calibration error at the low- and mid-levels will be ≤5 % of the calibration gas value.
   - At the end of a test run, a post-test calibration error test will be done at the zero and midlevels.
   - If the calibration error check at zero or midlevel exceeds ±3 % of the analyzer span value, the test run will be considered invalid.
2. THC Analyzer Span
   - EPA Method 25A recommends that the span value for the THC monitor should be 1.5 to 2.5 times the applicable emission concentration.
   - The THC monitor's span will be such that the majority of the 1-minute THC concentration averages are between 20 and 80 % of the span value.
   - If any measured gas concentration exceeds the analyzer's span, the THC data from the run will be invalid.

B2.0 EPA Methods 1 and 2 - Velocity

For the selection of traverse points, the following requirements will be observed:

1. The stack or duct diameter will be larger than 12 inches.
2. The measurement location will be at least 2 duct diameters downstream and ½ duct diameter upstream from a flow disturbance.
3. The number of traverse points will be based on Figure 1-2 of Method 1.
4. No traverse point will be closer than 1 inch from the stack wall for stacks with diameters greater than 24 inches and no closer than 0.5 inch for stacks with diameters between 12 and 24 inches.

For velocity measurements, the following requirements will be observed:

1. Cyclonic or swirling flow cannot exist at the sampling location (i.e., based on a cyclonic flow check, the average of the yaw angles must be $\leq 20^{o}$).
2. The Type-S pitot tube will be made of stainless steel.
3. The OD of the pitot tube will be between 0.1875 and 0.375 inch.
4. The distance from the base of each leg of the pitot tube to its face-opening plane will be equal.
5. The face opening to face opening distance will be between 1.05 and 1.5 times the tube OD.
6. The face openings of each pitot leg will be aligned with each other.

7. If the pitot meets the above criteria, a pitot coefficient, C_p, value of 0.84 can be assigned.
8. A C_p value other than 0.84 will be used if the pitot tube is calibrated according to Sections 4.1.2 through 4.1.5 of Method 2.
9. After field use, the pitot will be examined to ensure that it still meets the design specifications.
10. The differential pressure gauge (e.g., oil manometer) for measuring velocity head will have a precision of 0.01 inch H_2O over the 0- to 1-inch scale and 0.1 inch H_2O over the 1- to 10-inch scale.
11. The differential pressure gauge will be level (if required) when readings are taken.
12. A post-test leak check of velocity head measuring system
    - will be done on both the impact and static pressure sides of the pitot tube,
    - a velocity pressure of at least 3 inches of H_2O will be applied, and
    - for a passing leak check, the pressure reading will remain stable for at least 15 seconds.
13. A temperature gauge (e.g., thermocouple) for measuring stack gas temperature will measure to within ±1.5 % of the reference temperature value.
14. A barometer for measuring atmospheric pressure will measure to within ±0.1 inch of Hg against a mercury barometer.

B3.0 EPA Method 4 - Moisture

For the measurement of stack gas moisture content, the following requirements will be followed:

1. The sampling probe will be made of stainless steel or glass and sufficiently heated to prevent condensation.
2. A condenser, consisting of four impingers, will be used to remove moisture from the sample gas, with the impinger characteristics noted below:
    - the second impinger will be a Greenburg-Smith design with the standard tip,
    - the other three impingers will have a straight tube (modified Greenburg-Smith),
    - the first and second impingers will contain known volumes of water,
    - the third impinger will be empty, and
    - the fourth impinger will contain approximately 200 grams of indicating silica gel.
3. A minimum total sampled volume of 21 scf will be collected.
4. The temperature at the outlet of the silica gel impinger will be maintained at less than 68°F.
5. The sampling system will be leak-checked at the end of each test run as follows:
    - a vacuum of greater than 15 inches of Hg or greater than the highest vacuum observed during the test run, whichever is less, will be applied and
    - for an acceptable leak-check, the leak rate will be $\leq$0.02 cfm.
6. The volume of water collected will be recorded to the nearest 1 mL or 0.5 g.
7. The dry gas meter calibration will consist of:
    - three runs at a single, intermediate orifice setting based on the test data,
    - a vacuum setting at the highest value observed during the test runs, and
    - the average post test meter calibration factor, γ, must be within ±5 % of the pre-test γ.

8. The calibration of the dry gas meter and condenser outlet thermocouples will reference the thermocouples:
   - against a mercury-in-glass thermometer and
   - each thermocouple must agree to within ±1.5 % of the reference value.

B4.0 Ozone Sampling: NIOSH Method 154 or APHA Method 820

The QC procedures for these methods will closely follow those given in 40 CFR Part 60, Appendix A, Method 6.

For the sample volume metering system, a post-test meter calibration check will be performed. This calibration check will be done with a calibrated orifice, a calibrated dry gas meter, or a wet test meter. Two independent runs will be made over a sample volume of at least 3 L at a sampling rate of 1 L/min. If the calibration factor, γ, is within ± 5 % of the initial γ, then the dry gas meter volumes obtained during the test are acceptable. If the γ value deviates by > 5 %, the meter will be recalibrated, and the γ that gives the lower sample volume will be used for the calculations.

A pre- and post-test run leak-check of the sampling system will be conducted. For the leak check, a vacuum of at least 10 in. Hg will be applied to the system. A leak rate of ≤20 mL/min is acceptable. If a leak is found at the post-test leak-check, the run will be void.

During sampling, the following criteria will be maintained:

- constant sampling rate (± 10 %),
- readings of the dry gas meter, dry gas meter temperature, impinger outlet temperature, and rotameter taken every 5 minutes, and
- the temperature of the gas leaving the last impinger at ≤ 68°F.

After sampling, the impinger solutions will be transferred into an amber bottle, sealed, and the fluid level marked.

B5.0 QC Procedures for pH Meter

Properly maintaining the pH measuring system is important in achieving accurate and reliable pH measurements. The following QC procedures will be followed:

1. When not in use, the reference electrode will be stored in an acidic solution with a low salt content.
2. If a long stabilization time is needed for obtaining a pH reading, the reference electrode will be examined for proper operation following standard procedures.
3. If the reference electrode dries out, it will be restored following applicable procedures.

For an on-line pH monitoring system, an automatic cleaning system will be used to prevent deposits from forming on the reference electrode. If the sample solution contains small particles or fibers, the electrode assembly will be installed at an angle to the flow so that contaminants will not be trapped.

1. Laboratory pH Meter Calibration. The pH meter will be calibrated with freshly poured buffer solutions once each 8-hour shift at two calibration points, pH of 4.0 and 7.0, and before each series of measurements at one point, pH of 4.0.
2. On-line pH Meter Calibration. To avoid disassembling the on-line pH monitor's electrode, a self calibration system will be used.

B6.0 QC Procedures for Measuring Electrical Energy Requirements of Equipment

For the piece of equipment to be tested, determine the following:

3. type of electrical service (e.g., single-phase two-wire, three-phase three-wire),
4. voltage requirement (e.g., 120V, 240V, 480V),
5. full load power, and
6. current rating.

The metering system must be compatible with the type of electrical service and load. The electrical energy meter (W-hr or kW-hr) should have an accuracy of ±2 %. The precision and bias of ASTM E929-83 has not been established.

B7.0 Test Conditions Parameter Measurement Methods Quality Control

The methods used for monitoring the test condition parameters contain QC procedures and performance specifications. Those procedures and specifications for the applicable measurement methods are presented in this section.

B7.1 Thermocouple Temperature Measurement

The QC program for thermocouples will include operational QC practices and calibration practices.

1. Operational QC Practices for Thermocouples
   - All thermocouples used for this test program will be used in a sheath.
   - The operator will ensure that the thermocouple temperature readout, the device used to convert thermocouple voltage to temperature, is appropriate (i.e., has the same letter designation; J or K) for the thermocouple.
   - Thermocouple sensor system wires will not be located near motors, power supply cables, or other such electrically "noisy" equipment.
   - No hand-held radios will be used near the instrument.
   - Type J thermocouples will be used for temperature measurement only in the range of 32 to 1,400ºF.
   - Type K thermocouples will be used for temperature measurement only in the range of 32 to 2,300ºF.
2. Calibration QC Practices for Thermocouples
   - Calibration checks will be made at two points to confirm proper operation.
   - After a thermocouple fails, it will be replaced.
   - A comparative measurement of known temperatures with an ASTM certified

mercury thermometer will be done at two points within 6 months of the beginning of the test program at the following reference temperatures:

- S 32°F - ice water bath and
- S 212°F - boiling water (at 29.92 in. Hg)

- The temperature reading of the thermocouple must be within ±1.5 % of the reference temperature value.

B7.2 Infrared (IR) Thermometer Temperature Measurement

IR thermometers are somewhat sensitive to dirt, dust, flames, and vapors. Precautions will be taken to avoid damaging the IR thermometer by using sight tubes or clean surface mirrors to protect the sensor.

Measurement of an object's temperature will be limited to a distance of not more than 20 feet between the thermometer and the object. Also, the line of sight will be checked for other objects that may interfere with the radiation path. To overcome any line of sight problems, the instrument will be placed so that it is out of the geometric path of background radiation reflections or transmissions.

Calibration of the IR thermometer is done by measuring the temperature of a known target and adjusting the instrument to give the correct temperature. The reading of the IR thermometer must be within ±1.5 % of the reference temperature value. The emissivity of the target material must be accounted for during this calibration. One of two approaches will be followed:

1. A piece of masking tape will be placed on the target and the temperature of the masking tape measured with the IR thermometer, using an emissivity setting of 0.95. The temperature of the target will then be measured, and the emissivity compensator will be adjusted until the display shows the correct temperature.
2. Coat the target with flat black paint. The known target temperature will be measured with the emissivity set to 1.0, and the temperature reading will be reset to the correct value.

B7.3 Fluid Expansion Temperature Measurement

Only an alcohol-in-glass thermometer will be used to measure the temperature of ambient air. Care will be taken with the sling psychrometer to ensure that:

- both the wet bulb and dry bulb thermometers are securely attached before spinning,
- the spinning is done at a spot such that the thermometers cannot possibly contact anything and break, and
- the sling psychrometer will be stored such that the thermometers will not be broken by accident.

Calibration of the thermometer will be checked at two points with a NIST certified mercury thermometer:

- 32°F - in an ice water bath and
- 212°F - in boiling water (at 29.92 in. Hg).

The response of the thermometer must be within ±1.5 % of the reference temperature value.

B7.4 Orifice Plate for Fluid Flow Rate

Listed below are the QC requirements that will be followed for measuring fluid flow with an orifice plate.

1. Sufficient straight piping (at least 8 pipe diameters downstream of a disturbance and 4 pipe diameters upstream of a disturbance) upstream and downstream of the orifice plate should be present.
2. If flow pulsations are expected, a dampening chamber will be placed in the flow path near the pulsating equipment.
3. If used, a differential pressure transducer will be calibrated by simulating zero (4 mA) and span (20 mA) inputs to the transmitter,
4. The physical conditions of the bore of the orifice plate will be checked to ensure that dimensions are within tolerance (ASME MFC-3M-1989).
5. The location of the orifice pressure taps will be checked and the proper calibration or flow equation used.
6. An orifice plate flow meter may be used in pipe sizes up to 72 inches in diameter.
7. QA targets for meter accuracy will be set in the test/QA plan.

B7.5 Magnetic Flow Meter Fluid Flow Measurement

Listed below are the QC requirements that will be followed for measuring liquid flow with a magnetic flow meter.

1. The magnetic flow meter electronics will be calibrated before the test program (an AC magnetic flow meter must be calibrated at zero flow conditions with the flow meter full of liquid).
2. Magnetic flow meters may be used to measure liquid flow rates up to 150,000 gal/min (570,000 L/min).
3. Flow rate values will be checked to ensure they are within the measurement range specified for the meter.
4. A magnetic flow meter may be used in pipe sizes up to 96 inches in diameter.
5. QA targets for meter accuracy will be set in the test/QA plan.

B7.6 Positive Displacement Flow Meter Fluid Flow Measurement

Listed below are the QC requirements that will be followed for measuring fluid flow with a positive displacement flow meter.

1. The meter constant (K-factor) is fixed by meter design. The meter can be compared and calibrated against another volumetric flow instrument.
2. Before the test program, the converter will be checked and the zero and span will be set.
3. The flow rate values will be checked to ensure they are within the measurement range specified for the meter.
4. Positive displacement flow meters are highly accurate, within approximately ±0.2 % of the flow rate. Flow measurement QA requirements will be set in the test/QA plan.
5. Lobed-impeller flow meters may be used to measure liquid flow rates from 8 to 17,500 gal/min (30 to 66,000 L/min) in pipe sizes from 1.5 to 24 inches in diameter.
6. Helical gear meters may be used to measure liquid flow rates from 5 to 4,000 gal/min (19 to 15,000 L/min) in pipe sizes from 1.5 to 10 inches in diameter.
7. Slide vane rotary and retracting vane rotary flow meters may be used to measure liquid flow rate in pipe sizes up to 16 inches and up to only 4 inches in diameter, respectively.

B7.7 Turbine Flow Meter Fluid Flow Measurement

Listed below are the QC requirements that will be followed for measuring fluid flow with a turbine flow meter.

1. The primary flow meter device will be calibrated at the factory.
2. The meter's transmitter will be calibrated before the test program by simulating the frequency that the primary device would transmit at zero flow and maximum flow.
3. Turbine flow meters may be used to measure liquid flow rates up to 50,000 gal/min (189,000 L/min) and gas flow rates from 100 to 230,000 scfm.
4. Flow rate values will be checked to ensure they are within the measurement range specified for the meter.
5. A turbine flow meter may be used in pipe sizes up to 24 inches in diameter.
6. QA targets for meter accuracy will be set in the test/QA plan.

B7.8 Vortex Shedding Flow Meter Fluid Flow Measurement

Listed below are the QC requirements that will be followed for measuring fluid flow with a vortex shedding flow meter.

1. The primary flow meter device will be factory-calibrated.
2. The meter's transmitter will be calibrated before the test program by inputting frequency signals into the transmitter and making the appropriate adjustments.
3. A vortex shedding flow meter may be used for measuring liquid flow from about 3 to 50,000 gal/min (11 to 189,000 L/min) with a minimum flow rate for gases of about 60 scfm.
4. Flow rate values will be checked to ensure they are within the measurement range specified for the meter.
5. A vortex shedding flow meter may be used in pipe sizes from about 1 to 12 inches in diameter.
6. QA targets for meter accuracy will be set in the test/QA plan.

B7.9 Coriolis Mass Flow Meter Fluid Flow Measurement

Listed below are the QC requirements that will be followed for measuring fluid flow with a Coriolis mass flow meter:

1. Before the test program, the zero and span will be checked digitally under zero flow conditions and at the expected operating temperature.
2. The meter will be used at a temperature within ±50°F of the calibration temperature to prevent a reduction in accuracy.
3. Flow rate values will be checked to ensure they are within the measurement range specified for the meter.
4. Coriolis flow meters are limited to pipe sizes of about 6 inches or less in diameter.
5. QA targets for meter accuracy will be set in the test/QA plan.

B7.10 Aneroid Barometer Ambient Pressure Measurement

The aneroid barometer for measuring atmospheric pressure will be calibrated before the test program to ensure an accuracy within ±0.1 in. Hg against a mercury barometer. The barometer will be adjusted to within ±0.01 in. of the mercury barometer reading.

APPENDIX C: STATISTICAL ANALYSIS OF HYPOTHETICAL DATA SETS

This appendix contains example statistical analysis calculations for three hypothetical data sets, all of which arise from the hypothetical verification test plan described in Section 5.1.5. Appendix C is an expansion of Section 6.3. Taken together, the three data sets are thought to represent a reasonable range of potential outcomes for a verification test. The first three sections below (data sets No. 1, 2, and 3, respectively) present example calculations using outlet NOx as the performance measure. Data set No. 1 has the least variability in the data, followed by increasing variability in data sets No. 2 and 3. A fourth section presents an example calculation for data set No.1 using removal efficiency as the performance measure. The statistical analysis of variance presented in the sections below can be done using a number of statistical programs. It is assumed that the evaluator has access to commercial statistical analysis software such as SYSTAT, SPSS, SAS, STATA, or equivalents. The calculations in this protocol were performed using SYSTAT, Version 8.0, available from SPSS Corporation.

C1.0 Outlet NOx as the Performance Measure - Data Set No. 1

Table C-1 shows the hypothetical data set No.1 for two replicates of the 2x2x2 factorial design discussed in Section 5.1.5. The first step of the statistical analysis is to perform a three-factor (i.e., parameter) analysis of variance on these data. The dependent variable or response is the outlet NOx in ppmv denoted by OUT NOx in the table. The three measured, independent parameters are the inlet NOx level (IN NOx), the gas flow at the inlet to the reaction chamber (FLOW), and the temperature in the reaction chamber (TEMP). These three parameters are each grouped into low and high values, for this analysis. The mean low and high levels are given in the final two rows of Table C-1.

Table C-1. Hypothetical Data Set No. 1

RUN	IN NOx (ppmv)	FLOW (cfm)	TEMP (°F)	OUT NOx (ppmv)
1	55.1	21,000	285	1.22
2	54.7	29,000	290	1.32
3	53.8	20,000	320	1.11
4	55.3	29,500	325	1.26
5	287	20,500	283	8.70
6	290	30,000	287	10.2
7	292	20,000	303	9.10
8	291	28,500	306	9.70
9	52.8	20,400	289	1.12
10	51.6	30,100	291	0.98
11	53.1	20,800	312	1.21
12	52.5	29,600	315	1.26
13	291	20,200	290	7.80
14	294	30,200	292	9.20
15	289	21,100	306	8.10
16	290	31,000	309	9.50
Mean LO	**53.6**	**20,050**	**288**	

The results of the analysis of variance are shown in Table C-2. The full model includes the three main parameters and all of their interactions.

To interpret the analysis of variance in Table C-2, look at the column headed "P-value significance." Values of or less than 0.05 indicate a statistical significance of the parameter at the 95% significance level or above. Two main parameters, IN NOx and FLOW, and their interaction are statistically significant, although

Table C-2. Analysis of Variance for Full Model on Data Set No. 1

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	246.647	1	246.647	1321.795	0.000
TEMP	0.031	1	0.031	0.164	0.696
FLOW	1.600	1	1.600	8.576	0.019
IN NOx * TEMP	0.006	1	0.006	0.030	0.866
IN NOx * FLOW	1.404	1	1.404	7.525	0.025
TEMP * FLOW	0.027	1	0.027	0.146	0.712
IN NOx * TEMP * FLOW	0.081	1	0.081	0.435	0.528
Error	1.493	8	0.187		
Standard Deviation		8	0.432		

Notes: Dep Var: OUT NOx, N: 16, Multiple R: 0.997, Squared multiple R: 0.994

IN NOx is clearly the most important effect.

The next step is to repeat the analysis of variance for a reduced model including only the two significant main parameters and their interaction. The output from this step is shown in Table C-3.

Table C-3. Analysis of Variance Output for Reduced Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	246.647	1	246.647	1807.490	0.000
FLOW	1.600	1	1.600	11.727	0.005
IN NOx * FLOW	1.404	1	1.404	10.291	0.008
Error	1.637	12	0.136		
Standard Deviation		12	0.369		

Notes: Dep Var: OUT NOx, N: 16, Multiple R: 0.997, Squared multiple R: 0.993

Both parameters, IN NOx and FLOW, individually and their interaction remained statistically significant. Table C-4 shows the least square means for each level (low and high) of the two main parameters and for their interaction. The mean OUT NOx level was about 1.2 ppmv for low IN NOx levels compared to 9.0 ppmv for high IN NOx levels. If these means are calculated separately for the low and high flow conditions, the difference between the two OUT NOx values is slightly smaller at low flow and slightly larger at high flow. The difference between the OUT NOx means for the low and high flow conditions was modest: 4.8ppmv at low flow compared to 5.4 ppmv at high flow. The small variability in the data, represented by a small standard deviation estimated at 0.37 ppm, is the reason that the relatively small differences by flow and the interaction were statistically significant.

Table C-4. Least Squares Means for Reduced Model for Data Set No. 1

Parameter or Interaction - Level	OUT NOx least square mean, ppmv	Standard error	N
IN NOx - Low	1.185	0.131	8
IN NOx - High	9.038	0.131	8
FLOW - Low	4.795	0.131	8
FLOW - High	5.427	0.131	8
IN NOx - Low, FLOW - Low	1.165	0.185	4
IN NOx - High, FLOW - Low	8.425	0.185	4
IN NOx - Low, FLOW - High	1.205	0.185	4
IN NOx - High, FLOW - High	9.650	0.185	4

At this point a decision can be made as to whether the differences in OUT NOx values observed were large enough to be of practical importance. If not, those parameters that led to unimportant differences would be dropped from the analysis and a further reduced model would be fit. If all differences were judged important, then the results would indicate that the control device performs differently for different IN NOx levels and different flow rates. The performance would be estimated separately for each such combination.

For purposes of illustration, assume that 1) the differences in OUT NOx values observed were large enough and 2) only the effect of IN NOx is large enough to be of interest. (The flow rate can be chosen for analysis in the same manner as the following analysis of IN NOx.) Two approaches can be used for this analysis. One is to fit a model with IN NOx as the only parameter. The results are shown in Table C-5. The estimated results would be presented separately for the low and high IN NOx levels. Confidence intervals for the OUT NOx level can be calculated by taking the mean for each IN NOx level and adding and subtracting the 95% t-value with 14 degrees of freedom times the standard error indicated in the table.

A second approach to estimating the effectiveness of the control device is to perform a regression of OUT NOx on IN NOx. The result is an equation of the form

$$\text{OUT NOx} = a + b * \text{IN NOx}$$

that can be used to predict the OUT NOx as a function of IN NOx. The result of the regression is given in Table C-6.

The estimated value of a, the intercept, is -0.593 while that of b, the slope, is 0.033. Thus, the predicted equation is

$$\text{OUT NOx} = -0.593 + 0.033\ (\text{IN NOx})$$

This equation should only be used over approximately the range of inlet NOx values observed; i.e., about 50 to 290 ppm.

Table C-5. Analysis of Variance Output for Further Reduced Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	246.647	1	246.647	743.881	0.000
Error	4.642	14	0.332		
Standard Deviation		14	0.576		
Parameter or Interaction - Level	OUT NOx least square mean, ppm	Standard error	N		
IN NOx - Low	1.185	0.204	8		
IN NOx - High	9.038	0.240	8		

Notes: Dep Var: OUT NOx, N: 16, Multiple R: 0.991, Squared multiple R: 0.982

Table C-6. Regression Output

Constant or Parameter	Coefficient	Standard error	t	P-value (2 Tail)
Constant	-0.593	0.250	-2.373	0.032
IN NOx	0.033	0.001	27.706	0.000
Constant or Parameter	Coefficient	Lower <95%> Upper		
Constant	-0.593	-1.129 -0.057		
IN NOx	0.033	0.031 0.036		

Notes: Dep Var: OUT NOx, N: 16, Multiple R: 0.991, Squared multiple R: 0.982
Adjusted squared multiple R: 0.981, Standard error of estimate: 0.567

C2.0 Outlet NOx as the Performance Measure - Data Set No. 2

Table C-7 shows hypothetical data set No. 2, which has more variability than data set No. 1, particularly in the IN NOx and OUT NOx values. The same three-factor analysis of variance is performed as for data set No. 1. The parameters are the same; however, the low and high values in the bottom two rows reflect the new data set.

The analysis of variance output for this data set is shown in Table C-8.

As for data set No. 1, the IN NOx level was significant and the interaction between flow and temperature might be significant. However, since the independent parameters of FLOW and TEMP are not significant, their interaction is not considered significant. A reduced model for IN NOx was fit with the results shown in Table C-9. The analysis of data set No. 3 below will include, for illustration, an intermediate step of fitting a reduced model for IN NOx, FLOW (the next most significant parameter), and their interaction to check the significance of these effects.

Table C-7. Hypothetical Data Set No. 2

RUN	IN NOx (ppmv)	FLOW (cfm)	TEMP (°F)	OUT NOx (ppmv)
1	51.5	21,000	285	1.22
2	61.5	29,000	290	2.30
3	53.8	19,600	320	1.11
4	57.3	29,500	325	2.26
5	287	20,500	283	4.70
6	304	30,000	287	15.2
7	292	20,000	303	14.1
8	315	28,500	306	5.70
9	50.8	20,400	289	0.98
10	51.6	30,100	291	3.21
11	53.1	20,800	312	3.93
12	52.5	29,600	315	2.89
13	291	20,200	290	4.01
14	322	30,200	292	10.2
15	289	21,100	306	8.10
16	312	31,000	309	9.50
Mean LO	**54.0**	**20,450**	**288.4**	
Mean HI	**301.5**	**29,740**	**312**	

Table C-8. Analysis of Variance Output for Full Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	179.627	1	179.627	33.752	0.000
TEMP	2.081	1	2.081	0.391	0.549
FLOW	10.742	1	10.742	2.018	0.193
IN NOx * TEMP	0.041	1	0.041	0.008	0.932
IN NOx * FLOW	2.457	1	2.457	0.462	0.516
TEMP * FLOW	45.192	1	45.192	8.492	0.019
IN NOx * TEMP * FLOW	26.240	1	26.240	4.931	0.057
Error	42.576	8	5.322		
Standard Deviation		8	2.307		

Notes: Dep Var: OUT NOx, N: 16, Multiple R: 0.929, Squared multiple R: 0.862

Table C-9. Analysis of Variance Output for Further Reduced Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	179.627	1	179.627	19.445	0.001
Error	129.328	14	9.238		
Standard Deviation			3.039		
Parameter or Interaction - Level	OUT NOx least square mean, ppm	Standard error	N		
IN NOx - Low	2.237	1.075	8		
IN NOx - High	8.939	1.075	8		

Notes: Dep Var: OUT NOx, N: 16, Multiple R: 0.762, Squared multiple R: 0.581

IN NOx was statistically significant, indicating that the performance of the control device is such that OUT NOx depends on IN NOx. Separate confidence intervals for the mean OUT NOx level can be calculated for the two levels of IN NOx. These calculations gave the 95% confidence interval for the mean OUT NOx as 0 to 4.5 ppmv (2.2 ± 2.3) for the lower IN NOx level and 6.6 to 11.2 ppmv (8.9 ± 2.3) for the higher IN NOx level. In this case, the DQOs are not met at either NOx level.

For purposes of illustration, suppose that the difference between the levels 2.2 and 8.9 is not considered important. Then a single OUT NOx value could be estimated using the overall mean. A confidence interval for the mean OUT NOx is computed using the mean and standard error of the mean together with the t-statistic. The result is considered valid for the range of IN NOx used in the performance testing. The results are shown in Table C-10. Here the computed confidence interval is from 3.2 to 8.0 ppm. Notice that this confidence interval covers a range in between the means for the low and high groups. This is because of the significant difference between the groups. The confidence interval is only valid for a smaller range of IN NOx values than the full measured range.

If a significant dependence is found on one of the factors, the performance estimates should account for this, or the performance must be restricted to a smaller range for that factor.

Table C-10. Confidence Intervals for a Single Output NOx Level

	OUT NOx (ppmv)
N	16
Mean	5.6
95% CI Upper	8.0
95% CI Lower	3.2
Standard Error	1.135
Standard Deviation	4.538

C3.0 Outlet NOx as the Performance Measure - Data Set No. 3

The hypothetical data set No. 3 is shown in Table C-11. Relative to data set No. 2, this data set has increased variability in the OUT NOx column. The parameters and analysis of variance are the same as for data sets No. 1 and 2. Table C-12 contains the analysis of variance.

As with the other data sets, only the IN NOx parameter was significant at the 5% level. The two-way interaction between TEMP and FLOW and the three-way interaction were marginally significant. A reduced model was fit using IN NOx and FLOW and their interaction with the result shown in Table C-13. In selecting the reduced model, the main effect of IN NOx was included since it was statistically significant. The main effect of FLOW was the next most important variable, so it was included. The two-way interaction between IN NOx and FLOW was also included to see if it was significant. The marginally significant two-way interaction between FLOW and TEMP and the marginally significant three-way interaction in Table C-12 were not included. The reason is that neither of the main effects (FLOW or TEMP) was significant. It is common statistical practice to ignore a marginally significant interaction if neither main effect is significant. The results in Table C-13 show that only the effect of IN NOx was statistically significant. Thus, the final model shown in Table C-14 included IN NOx as the only parameter.

Table C-11. Hypothetical Data Set No. 3

RUN	IN NOx (ppmv)	FLOW (cfm)	TEMP (°F)	OUT NOx (ppmv)
1	51.5	21000	285	1.22
2	61.5	29000	290	2.30
3	53.8	19600	320	1.11
4	57.3	29500	325	2.26
5	287	20500	283	4.70
6	304	30000	287	16.2
7	292	20000	303	17.1
8	315	28500	306	5.70
9	50.8	20400	289	0.98
10	51.6	30100	291	3.21
11	53.1	20800	312	4.23
12	52.5	29600	315	5.46
13	291	20200	290	3.81
14	322	30200	292	12.2
15	289	21100	306	8.10
16	312	31000	309	9.50
Mean LO	**54.0**	**20,450**	**288**	
Mean HI	**301.5**	**29,738**	**312**	

Table C-12. Analysis of Variance Output for Full Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	199.798	1	199.798	24.019	0.001
TEMP	4.884	1	4.884	0.587	0.466
FLOW	15.171	1	15.171	1.824	0.214
IN NOx * TEMP	0.216	1	0.216	0.026	0.876
IN NOx * FLOW	1.102	1	1.102	0.133	0.725
TEMP * FLOW	59.367	1	59.367	7.137	0.028
IN NOx * TEMP * FLOW	52.418	1	52.418	6.302	0.036
Error	66.546	8	8.318		
Standard Deviation		8	2.884		

Notes: Dep Var: OUT NOx, N: 16, Multiple R: 0.913, Squared multiple R: 0.833

Table C-13. Analysis of Variance Output for Reduced Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	199.798	1	199.798	13.071	0.004
FLOW	15.171	1	15.171	0.992	0.339
IN NOx * FLOW	1.102	1	1.102	0.072	0.793
Error	183.431	12	15.286		
Standard Deviation			3.910		

Notes: Dep Var: OUT NOx, N: 16, Multiple R: 0.735, Squared multiple R: 0.541

The small P-value in Table 14 shows that the effect of IN NOx concentration on OUT NOx concentration was highly significant. Since essentially only two IN NOx concentrations were used, confidence intervals for the OUT NOx concentration can be estimated separately for each inlet level by taking the reported least squares mean and adding and subtracting the standard error times the t-distribution value with 14 degrees of freedom.

Since there was a significant difference by the two levels of IN NOx, OUT NOx should be reported separately for each IN NOx level. The 95% confidence limits were calculated by multiplying the standard error for each mean by the value from the t-distribution with 14 degrees of freedom. Then this value is subtracted and added to the mean to get the confidence limits. Note that it is possible to calculate a negative value for the lower limit. If this occurs, it should be reported as zero, since logically a concentration must be non-negative. The results of this calculation gave the 95% confidence interval for the mean OUT NOx as 0 to 5.5 ppmv for the lower level of IN NOx and 6.8 to 12.5 ppmv for the higher level of IN NOx concentration. Again, the DQOs are not met.

Table C-14. Further Reduced Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	199.798	1	199.798	14.007	0.002
Error	199.705	14	14.265		
Standard Deviation		14	3.777		
Parameter or Interaction - Level	OUT NOx least square mean, ppm	Standard error	N		
IN NOx - Low	2.596	1.335	8		
IN NOx - High	9.664	1.335	8		

Notes: Dep Var: OUT NOx, N: 16, Multiple R: 0.707, Squared multiple R: 0.500

C4.0 Removal Efficiency as the Performance Measure - Data Set No. 1

This example uses the same data set No. 1 as presented in Table C-1. The statistical analysis is also similar except the dependent variable is the removal efficiency (RE). The three parameters are the same and the same factorial design is used. Table C-15 shows the efficiencies calculated from the data in Table C-1 and Table C-16 shows the results of the analysis of variance.

Table C-15. Calculated Removal Efficiencies for Data Set No. 1

Run	RE (%)
1	97.826
2	97.623
3	97.922
4	97.688
5	96.962
6	96.484
7	96.891
8	96.666
9	97.925
10	98.112
11	97.724
12	97.574
13	97.315
14	96.870
15	97.206
16	96.722

Table C-16. Analysis of Variance Output for Full Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	3.312	1	3.312	78.374	0.000
TEMP	0.033	1	0.033	0.774	0.405
FLOW	0.258	1	0.258	6.107	0.039
IN NOx * TEMP	0.012	1	0.012	0.273	0.615
IN NOx * FLOW	0.095	1	0.095	2.244	0.172
TEMP * FLOW	0.001	1	0.001	0.035	0.857
IN NOx * TEMP * FLOW	0.021	1	0.021	0.502	0.499
Error	0.338	8	0.042		

Notes: Dep Var: RE, N: 16, Multiple R: 0.958, Squared multiple R: 0.917

Table C-16 shows that two main effects, for IN NOx and for FLOW, are statistically significant at the 5% level, although it is clear that the effect of IN NOx is much more important. The analysis of variance is repeated including only the two significant parameters, IN NOx and FLOW. The output from this step is shown in Table C-17.

Table C-17 shows that both parameters remain significant at the 5% level. However, the effect of flow is not significant at the 1% level. The means for each level of the two factors are calculated and shown in Table C-18. The standard error associated with each mean and the number of observations used to calculate each mean are also shown. At this point a decision must be made whether to keep the effect of flow in reporting the results. If the chosen significance level were 1%, this factor would not be significant and would be dropped. Even when it is significant, inspection of the two mean removal efficiencies shows a very small. difference that may not be of practical importance. If the decision is made to not include the parameter FLOW in reporting, then a final analysis of variance model would be run including only the parameter IN NOx.

Table C-17. Analysis of Variance Output for Reduced Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	3.312	1	3.312	78.374	0.000
FLOW	0.258	1	0.258	6.712	0.022
Error	0.500	13	0.038		

Table C-18. Least Squares Means

Parameter - Level	NOx removal efficiency least square mean (%)	Standard error (%)	N
IN NOx - Low	97.799	0.069	8
IN NOx - High	96.889	0.069	8
FLOW - Low	97.471	0.069	8
FLOW - Low	97.217	0.069	8

The results of dropping the variable parameter FLOW are shown in Table C-19. The mean removal efficiency for each level is shown at the bottom of the table. The effect of the two levels of IN NOx is highly significant. However, the removal efficiencies are not extremely different at 97.8% for low IN NOx and 96.9% for high IN NOx levels.

Assuming that the low and high levels are reported separately, a 95% confidence interval for each removal efficiency would be calculated and reported along with the estimated removal efficiency. Since the final model error term has 14 degrees of freedom, the critical value from the t-table with 14 degrees of freedom is used, giving a two-sided value of ±2.145. (This is the upper 97.5-percentile for the t-distribution.) The confidence interval is found by adding and subtracting the t-value times the standard error to the estimated removal efficiency. In this example, one would report that the removal efficiency depended on the IN NOx concentration, which ranged from about 55 ppmv at the low level to about 290 at the high level. The estimated removal efficiency for the low level of IN NOx was 97.8% ± 0.2%, or from 97.6% to 98.0%. The removal efficiency at the higher NOx level was estimated as 96.9% ± 0.2%, or from 96.7% to 97.1%.

It would also be possible to decide that the difference in removal efficiency for the IN NOx levels was too small to be of practical importance. In this case, the overall mean removal efficiency and its 95% confidence interval would be calculated and reported.

Table C-19. Analysis of Variance Results for Final Model

Parameter or Interaction	Sum-of-squares	Degrees of freedom	Mean-square	F-ratio	P-value significance
IN NOx	3.312	1	3.312	61.176	0.000
Error	0.758	14	0.054		

Parameter - Level	NOx removal efficiency least square mean (%)	Standard error (%)	N
IN NOx - Low	97.799	0.082	8
IN NOx - High	96.889	0.082	8

APPENDIX D: EXAMPLE VERIFICATION STATEMENT

Appendix D is an example verification statement for an ozone-injection NOx control technology. It is intended to show the form of a verification statement and will require modification for each technology verified, depending on the details of that technology's design, construction, and operation. The test/QA plan will include a draft verification statement customized for the technology being tested.

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

Research Triangle Institute

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**ADD-ON NOx AIR POLLUTION CONTROL TECHNOLOGY**		
APPLICATION:	**CONTROL OF NOx EMISSIONS FROM COMBUSTION SOURCES USING OZONE INJECTION**		
TECHNOLOGY NAME:	**TECHNOLOGY NAME**		
COMPANY:	**COMPANY NAME**		
ADDRESS:	**ADDRESS** **CITY, STATE ZIP**	**PHONE:** **FAX:**	**(000) 000-0000** **(000) 000-0000**

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups which consist of buyers, vendor organizations, permitters, and other interested parties; with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Air Pollution Control Technology (APCT) program, one of 12 technology areas under ETV, is operated by the Research Triangle Institute (RTI), in cooperation with EPA's National Risk Management Research Laboratory. The APCT program has evaluated the performance of an add-on NOx control technology utilizing ozone injection for stationary combustion sources, TECHNOLOGY NAME.

VERIFICATION TEST DESCRIPTION

All tests were performed in accordance with general guidance given by the APCT program Generic Verification Protocol for Add-On NOx Control Technologies Utilizing Ozone Injection for Stationary Combustion Sources" and the specific technology test plan "Verification Test/QA Plan for TECHNOLOGY NAME". These documents include requirements for quality management, quality assurance, procedures for product selection, auditing of the test laboratories, and test reporting format.

The NOx Emission Control Technology was tested as installed and operating at a field test site using stack test methods. NOx concentrations were measured using continuous emissions monitors (CEMs) following EPA Method 7E. Other gaseous emissions were monitored using the applicable EPA test method. Flow rates, temperatures, and other process variables were monitored using calibrated plant instrumentation.

Tests were conducted to meet primary quality assurance goals of a 95% confidence interval with a width of ±5% or less of the mean NOx emission concentration for concentrations above 5 ppmv (±20% for emission concentrations below 5 ppmv). The verification test is valid only for the stated performance envelope of process temperature, inlet NOx concentration, and flow rate.

A single test run consisted of setting the primary process variables of flow rate, inlet NOx, and temperature, allowing the process to reach steady-state, and then measuring outlet NOx concentration over a half-hour steady-state process condition. The test design was a 2 x 2 x 2 factorial using two levels of temperature, inlet NOx, and flow rate. The limits of the performance envelope within which the verification is valid are set by the values of these independent variables, as shown in Table 1.

Table 1. Example verification test performance envelope

	Temperature, °C (°F)	**Inlet NOx, ppmv**	**Flow Rate, m^3/min (cfm)**
Low			
High			

In addition to outlet NOx concentration and the primary process variables, a number of other emissions of importance for ozone-injection NOx control technologies were also measured using EPA standard methods, and the energy use rates, staffing, maintenance requirements, and similar issues were noted qualitatively.

TECHNOLOGY DESCRIPTION

This verification statement is applicable to the TECHNOLOGY NAME, which is one of several proprietary technologies that react ozone with NOx and scrub the resulting nitric acid. The ozone is injected into the flue gas with the desired stoichiometry. The reaction zone residence time required depends on the temperature of the flue gas and varies depending on whether the technology recovers heat before or after ozone injection. The insoluble stack gas NOx (largely NO and NO_2) reacts with the ozone to form N_2O_5, which is soluble in water. A scrubber at the end of the train collects the N_2O_5 and any gaseous HNO_3 into an acid waste stream. In addition to NOx removal, such technologies have potential for removal of other acid gases (SO_2 and CO) and VOCs. Control of these other pollutants is not a topic included in this generic verification protocol.

This verification statement covers application of TECHNOLOGY NAME to small- and medium-sized stationary combustion sources fueled by natural gas.TECHNOLOGY NAME is characterized by injection of the ozone ....
....
....
....
....

VENDOR'S STATEMENT OF PERFORMANCE

TECHNOLOGY NAME is capable of achieving a NOx emission concentration of _____ ppmv when operated at an inlet NOx concentration of _____ ppmv and [specify process operating conditions] and of controlling NOx emissions to below _____ ppmv when operated at an an inlet NOx concentration of _____ ppmv and [specify different process operating conditions].

VERIFICATION OF PERFORMANCE

Verification testing of TECHNOLOGY NAME was performed from _____ through _____, at an installation on a natural-gas-fired combustion source in State or Region. The results are given in Table 2.

TECHNOLOGY NAME

Table 2. NOx control performance

Inlet NOx Concentration ppmv	Temperature at Ozone Injection Site °C (°F)	Flow Rate m^3/min (cfm)	Mean Outlet NOx Concentration ppmv	Half-Width of 95% Confidence Interval on Mean Outlet NOx ppmv

The APCT quality assurance (QA) Officer has reviewed the test results and quality control data and has concluded that data quality objectives given in the generic verification protocol and test/QA have been attained.

During the verification tests, EPA and/or APCT quality assurance staff conducted technical assessments at the test laboratory, which confirm that the verification test was conducted in accordance with the test laboratory's EPA-approved test/QA Plan.

This verification statement verifies the NOx emissions characteristics of TECHNOLOGY NAME within the stated range of application. Extrapolation outside that range should be done with caution and an understanding of the scientific principles that control the performance of TECHNOLOGY NAME. Users with NOx control requirements should also consider other performance parameters such as service life and cost when selecting a NOx control system.

In accordance with the generic verification protocol, this verification report is valid indefinitely for application of TECHNOLOGY NAME within the range of applicability of the statement.

E. Timothy Oppelt Date	Jack R. Farmer Date
Director	Program Manager
National Risk Management Research Laboratory	Air Pollution Control Technology Program
Office of Research and Development	Research Triangle Institute
United States Environmental Protection Agency	

NOTICE: ETV verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and RTI make no expressed or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of commercial product names does not imply endorsement.